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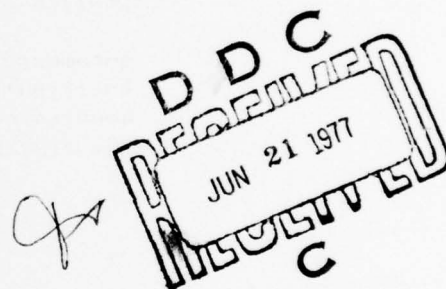
AVSCOM REPORT NO. DRS AV-76-30
PRODUCTION ENGINEERING MEASURES PROGRAM
MANUFACTURING METHODS AND TECHNOLOGY

ARMY AVIATION MANUFACTURING TECHNOLOGY PROGRAM GUIDANCE

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June 1976

Final Report



Approved for public release; distribution unlimited

Prepared for

US ARMY AVIATION SYSTEMS COMMAND
St. Louis, Missouri 63166

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FOREWORD

This final report on "Army Aviation Manufacturing Technology Program Guidance" covers the work performed under Manufacturing Methods and Technology Project 1748138, Contract DAAJ01-75-C-0448 (PlG) with Battelle's Columbus Laboratories during the period February 1, 1975, to May 17, 1976.

This program has been conducted in the Metalworking Section of Battelle's Columbus Laboratories with Mr. T. G. Byrer, Section Manager. Project Manager was Mr. H. J. Henning, Research Leader, Department of Metallurgy. Mr. B. R. Noton, Research Leader, Structures and Mechanics Department was a major contributor to the sections of the report dealing with composites. Other participants included Mr. M. D. Randall and Dr. R. S. Williams of the Fabrication and Quality Assurance Section. Other Battelle specialists were consulted as appropriate for information about specific technical areas.

This project was monitored by Mr. Roger Spangenberg of the AVSCOM Production Technology Branch. The AVSCOM Production Technology Branch is headed by Mr. Robert Vollmer, Chief.

The recommendations obtained as a result of technical discussions with representatives of several companies provided valuable input to this report.

In alphabetical order, the companies visited during the field interviews are as follows:

A

- Advanced Structures, Inc.
Monrovia, California
- Allison Division of General
Motors Company
Indianapolis, Indiana
- Bell Helicopters Textron
Fort Worth, Texas
- Boeing-Vertol Company
Morton, Pennsylvania
- Fiber Sciences, Inc.
Gardena, California
- General Electric Company
Lynn, Massachusetts
- Goldsworthy Engineering, Inc.
Torrance, California
- Hamilton Standard Division
United Technologies Corporation
Windsor Locks, Connecticut
- Hughes Helicopters Division
Summa Corporation
Culver City, California
- Lycoming Division
Avco Corporation
Stratford, Connecticut
- Sikorsky Aircraft Division
United Technologies Corporation
Stratford, Connecticut
- Ti-Tech International, Inc.
Pomona, California
- Wyman Gordon Company
North Grafton, Massachusetts.

The Government organizations contacted during the field interviews are as follows:

- Army Materials and Mechanics Research Center
Watertown, Massachusetts
- Army Aviation Systems Command
St. Louis, Missouri
 - Production Technology Branch
 - UTTAS Project Manager Office
 - AAH Project Manager Office
 - AH-1 (Cobra) Project Manager Office
 - CH-47 MOD Project Manager Office
- Corpus Christi Army Depot
Corpus Christi, Texas
- Wright-Patterson Air Force Base
Dayton, Ohio.

Comprehensive data received during these visits have been incorporated in this report. Cooperation provided by these organizations and the individuals we contacted is gratefully acknowledged.

In addition, Battelle project staff members have attended the following important meetings and conferences:

- American Helicopter Society 31st Annual Forum
(Washington, D.C.)
- International Conference on Composites
(Philadelphia, Pennsylvania)
- Air Force Briefing on Composites -- Development
of Cost Estimating Manual.
- Conference on Advanced Composites
(Washington, D.C.).

These activities provided useful background to the program.

This project was accomplished as part of the U.S. Army Aviation Systems Command Manufacturing Technology Program. The primary objective of this program is to develop, on a timely basis, manufacturing processes, techniques, and equipment for use in production of Army material. Comments are solicited on the potential utilization of the information contained herein as applied to present and/or future production programs. Such comments should be sent to: U.S. Army Aviation Systems Command, ATTN: DRSAVEXT, P.O. Box 209, St. Louis, MO 63166.

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SUMMARY

An overall goal for the Production Technology Branch of AVSCOM is to carry out Manufacturing Methods and Technology (MM&T) programs which assure that the Army is able to acquire and operate helicopters with maximum performance and reliability for reasonable cost. Currently, AVSCOM asks the many suppliers of aircraft and components to offer suggestions for projects/programs which are individually aimed at this overall goal. Battelle was asked to assist AVSCOM by developing, on an impartial basis, an overall recommended manufacturing technology plan for the five-year time frame between FY 1977 and FY 1982.

Toward this end, Battelle first examined the "drivers" of helicopter cost; appropriate programs to attack these cost drivers should maximize the return on the Army's investments in manufacturing technology. As many Army Aviation manufacturing technology problems and potential solutions (or proposed projects) as possible were then identified and evaluated as to their effects on helicopter costs, state-of-the-art in development and several other factors. Finally, appropriate program areas or "thrusters" were defined and a program plan formulated.

As this project activity progressed it became apparent that some effort should be directed to examine the goals and objectives of the AVSCOM Production Technology Branch, how the suggested program would fit within the operating guidelines of that Branch, and how the future profile of the Branch might be altered to better meet the needs of industry in helicopter manufacture.

A review of suggested programs indicated that approximately 30 percent required manufacturing development monies before return on investment calculations could realistically be made and an MM&T program justified. Thus, recommendations are made that consideration be given to establishing a vehicle whereby Manufacturing Development (MD) funds can be made available for this purpose.

Another area where, heretofore, benefits have not been maximized is that of developing manufacturing technology for developmental systems as producibility studies identify areas for improvement. Consequently, recommendations are made that AVSCOM vigorously pursue the establishment of funding for this type effort.

Another important factor involved the transfer of technology on AVSCOM programs that have been carried out. Recommendations are made that frequent industry briefings be held on the technological findings of MD and MM&T programs and that an effective distribution system for project reports be established to assure that information is properly disseminated.

Along these same lines, it is recommended that consideration be given to initiating an Accelerated Implementation program for new technologies which promise excellent return on investment and for the solution of urgent problems. The sooner these types of developments are implemented the sooner helicopter costs can be reduced and this technology translated to newer helicopter designs further down the road.

Responding mainly to "bottom-up" project submissions from many firms does not provide for the development of a cohesive, proactive plan of manufacturing technology action designed to develop longer ranging solutions to longer ranging goals. Reaction and responsiveness to industry needs, of course, are important but can lead to a somewhat fragmented plan. It is believed important for AVSCOM to also have a more formal "top-down" plan giving consideration to those areas or "thrusts" where helicopter costs can be effectively attacked. AVSCOM's Production Technology Branch can then initiate actions where each accomplishment can complement the next within a given "thrust" area.

In starting the plan development, visits were made to various manufacturers of helicopters and components as well as repair/maintenance facilities to discuss a variety of topics ranging from specific problem areas to the overall policy of Army MM&T program management.

Important consideration was given to the cost drivers in helicopter manufacture -- where appropriate "thrusts" could have impact on acquisition and life-cycle costs. There are times when "unglamorous" programs can yield handsome returns on Army investment in MM&T. For example, maintainability and repairability is a major cost driver and an area for significant long-range cost reduction, but not a significant thrust area from the advanced materials/processes standpoint. On the other hand, experimental preparation of large rotor hubs and other large components from titanium alloy powders has been suggested, yet the prospects are slim for achieving properties as reproducibly high as obtained from forgings or for reducing costs.

The list of problems and potential solutions obtained from the various information sources contained over 275 items with the following approximate distribution:

<u>Subsystem</u>	<u>Distribution, percent</u>
Airframe	25
Engine	34
Rotor	24
Drive	13
Support Equipment	4

The unexpected large number of identifiable problems complicated the ranking and required suitable evaluation criteria to help reduce the list to manageable size.

The project effort then turned to the task of proposing important "thrust" areas where AVSCOM could assign budgets, identify appropriate project areas, and set cost reduction and technical goals to be reached within 5 years. Consideration was also given to the "thrusts" being supported by other branches of the Army and the Air Force manufacturing technology programs so that the AVSCOM program areas would complement rather than duplicate efforts already underway.

The 12 major thrusts defined are as follows:

- Composites
- Joining
- Repairability and Maintainability
- Computer Applications in Manufacturing
- Quality Control
- Reduction of Part Count
- Net Shape Processing
- Hot Isostatic Processing (HIP)
- Production Ready Tooling
- Materials Related Developments
- Forging
- Casting.

The importance of these thrusts is dependent upon helicopter subsystem. The thrust areas found most important for each subsystem are as follows:

<u>Airframe</u>	<u>Engine</u>	<u>Rotor</u>	<u>Drive</u>
Composites	Materials Related	Composites	Joining
Joining	Casting (plus HIP)	Production Tooling	Composites
Part Count	Joining	Joining	QC/NDT
Production Tooling	Net Shape (Forging)	QC/NDT	Forging
R and M	R and M	CAM	CAM
QC/NDT .			

These rankings of thrusts illustrate that the major emphasis initiated at AVSCOM should involve the following generic program emphasis or goals:

Airframe: Reduction of part count and labor costs through the development of production ready-tooling for manufacture of composite structures including important attention to joining and repairability

Engine: Improved performance of advanced materials cast and hot isostatic-processed to near-net shapes to reduce costs of turbine components. Production ready tooling will be especially important to the T-700 program as will suitable joining processes.

Rotor: Continuing improvements in manufacture of fiber reinforced and honeycomb composite structures, including important attention to production-ready tooling for manufacture, joining, and quality control (production and in-service) as applied to main and tail rotor blades for increasing reliability and reduced costs.

Drive: Development of methods for manufacturing improved, low-cost drive components and composite housings, including important attention to precision forging, nondestructive testing, and CAD/CAM.

Maintainability and repairability remain as vitally important project areas for reduction of life-cycle costs, especially as the newer models of helicopters reach production stages. These all represent important goals toward which AVSCOM can initiate and lead significant programs and experience good return on investment.

Approximate return-on-investment (ROI) analyses were conducted on those proposed projects where enough cost data could be obtained from contractors. The Army should experience an average ROI over the five year period of over 3:1 for the true MM&T projects. Estimates of ROI on the other projects were less clear. However, the manufacturing development projects and subsequent MM&T projects should lead to ROI over the five years of about 3:1 if the projects are selected carefully.

It should be recognized that most of the ROI estimates were based upon the premise that the currently planned purchasing schedules for specific helicopter models are reasonably firm through 1982. It is doubtful that many

of the suggested projects will experience a positive return on investment during the first 2 years of the 5-year period. The key factors in experiencing positive ROI on any of the manufacturing technology projects will be:

- (1) Effective technology transfer of project findings
- (2) Accelerated implementation of findings.

Based on the definition of some 55 projects which are considered to be implementation oriented with combined manufacturing development and MM&T funds, a funding guidance totalling 65.9 million dollars is projected for the period FY 77 to FY 82, with the following approximate breakdown by subsystem:

<u>Subsystem</u>	<u>Funding, percent</u>
Airframe	50
Engine	26
Rotor	12
Drive	12 .

This funding guidance is based on defined Manufacturing Technology thrust areas and provides guidance as to the extent of both Manufacturing Development and MM&T fund expenditures over the 5-year time frame.

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ARMY AVIATION MANUFACTURING TECHNOLOGY
PROGRAM GUIDANCE

by

H. J. Henning and T. G. Byrer

INTRODUCTION

In recent years the principles of the Department of Defense have changed from placing the overriding emphasis on producing hardware with state of the art performance to an emphasis on producing hardware "that can be acquired and owned at minimum and affordable cost, and which can be sufficient in performance".*

This means that emphasis in the next few years will be placed on applying existing materials and advanced fabrication technologies to the task of reducing costs and improving performance of helicopters and other Defense related hardware rather than on the development of advanced materials (which was the more common emphasis during the last two decades).

Over the years it has been proven to be in the best interest of the Department of Defense to support selected manufacturing technology related developments especially where there are few if any civilian markets to stimulate the independent development by private industry. Furthermore, even if the marketplace provides incentives for industry to conduct such efforts, the needed developments rarely coincide in time with the Defense Department need. Such developments usually come later. Moreover, such developments are carefully guarded by each company to keep ahead of competition. Some timely developments, which would otherwise be of value to the DoD, are virtually unknown until reasonably similar work is supported by the DoD.

* Statement of Principles for Department of Defense Research and Development.

Recognizing this and that a more cost-conscious philosophy will have an impact on the production of Army helicopters as well as on the scope of the Army's future manufacturing related programs, AVSCOM initiated this study aimed at formulating (1) a realistic five-year plan for developing and implementing advanced manufacturing technologies to the production of Army helicopters and (2) recommended modifications in the operation of the AVSCOM Manufacturing Technology program to realistically accommodate the plan.

It should be recognized that this planning document was prepared by Battelle as an independent analysis and that the guidance should be considered only as an overall guide to the identification of program areas. Emphasis described herein may change somewhat during the course of the five-year period depending on the needs of the Army and industry.

PROJECT METHODOLOGY

Listed below are six major steps pursued in carrying out this program:

- (1) Identify cost drivers
- (2) Obtain technical consensus/project suggestions
- (3) Conduct ratings of individual project suggestions
- (4) Conduct estimates of return on Army investment
- (5) Define overall technical thrust areas
- (6) Recommend project areas within each thrust.

This basic methodology serves as the basis for presentation of subsequent sections and recommendations found in the remainder of this report.

As a preliminary to evaluation and assessment of proposed projects in the development of a long range manufacturing technology plan for AVSCOM, attention was given to defining the major drivers of helicopter cost. This was accomplished through contacts with helicopter companies and component suppliers, repair and maintenance facilities and other Government activities. In the discussions held with company representatives, interrelationships between suggested project areas and the defined list of cost drivers provided a good basis for serious discussion of the potential for these projects to reduce the cost of helicopter manufacture.

As the data were being gathered, an evaluation system had to be defined and utilized so that a workable system could be established for evaluating projects submitted in the course of this program as well as providing a matrix for AVSCOM to utilize for future evaluation of suggested projects they receive. A part of this evaluation scheme involved calculation of potential return on investment if the project was carried to a successful conclusion and implemented into helicopter manufacture.

Major technical thrust areas were defined based upon the cost drivers and the project input, and the recommended project areas within each thrust were presented.

In the course of analyzing and studying the technical problems identified during the course of this program, it became apparent that consideration should also be given to:

- (1) Examining the scope of activity of the AVSCOM Production Technology Branch
- (2) Providing a mechanism and framework which would insure success in meeting current Branch goals and objectives and which would accommodate the proposed program guidance.

In order to best treat both the operational and technical findings of this program, the remainder of this report is divided into two major sections:

- Aviation Manufacturing Technology Program - Operational Guidance
- Aviation Manufacturing Technology Program - Technical Guidance.

The Operational Guidance section suggests how the Production Technology Branch methods of operation might be modified to better meet its goals and facilitate the solution to existing technical problems. The Technical Guidance section is the result of our analysis of the helicopter cost drivers and the many project suggestions, as well as our assessment of those program areas which appear to have the most promise in reducing the cost and/or improving the performance of helicopters over the next 5-year period. In essence then, the remainder of this report describes the work carried out and presents a summary of our findings in these two general areas of operational and technical guidance.

AVIATION MANUFACTURING TECHNOLOGY PROGRAM - OPERATIONAL GUIDANCE

CURRENT MANUFACTURING TECHNOLOGY PROGRAM OPERATION

An overall goal of AVSCOM's Manufacturing Technology Program is to assure that the Army maintains a solid manufacturing technology base for its current and future needs for modern aircraft on a cost-effective basis. AVSCOM currently asks the many suppliers of aircraft and components to offer suggestions for projects which are individually aimed at this overall goal. The manufacturing technology projects AVSCOM now supports are:

- Aimed at reducing manufacturing costs
- Directed to solving reasonably common problems (more than one system)
- Aimed at improving maintainability/reliability of current systems
- Assuring that production-ready equipment and facilities are ready at the time of production buys
- Aimed at implementing the results of promising IRAD efforts
- Aimed at applying CAD/CAM where cost effective in design, manufacture, and/or inspection
- Enabling informed decisions or choices to be made between candidate materials, processes, equipment, and/or designs
- Sometimes speculative in nature but where the potential payback is high in terms of low cost and/or improved performance.

Furthermore, AVSCOM has an important goal of getting the results of timely manufacturing technology projects into the hands of operating personnel who can apply the newly developed technologies in Army systems.

As a result of the Battelle study and the technical evaluations made, coupled with discussions with AVSCOM personnel and staff at the helicopter manufacturing companies, it is apparent that three major areas of concern involved (1) the high propensity for submission of projects to AVSCOM which are not within the true MM&T framework, (2) the long lead-times in obtaining funding for promising technology development, and (3) difficulties of new technology implementation into helicopter manufacture. In this portion of the report discussion is concentrated on possible resolution of the problems encountered from these three factors, and the existing goals and objectives of the Manufacturing Technology program are examined from the standpoint of possible expansion or alteration to help resolve these problems to the benefit of producing lower cost and/or improved performance helicopters.

ANALYSIS OF MANUFACTURING TECHNOLOGY PROGRAM FRAMEWORK

General

As a result of the project staff's discussions with the various AVSCOM contractors, it became apparent that there are two basic reasons that some project suggestions submitted are not within the true MM&T framework. First, it appears that guidelines for funding MM&T projects are too narrow to provide for all the effort necessary to bring a new manufacturing development to the point of implementation. Second, it appears that contractors need more technical guidelines as to the types of projects and/or areas which the Army is contemplating pursuing.

Funding Guidelines

Manufacturing Development

A principal goal of the Production Technology Branch has been to support Manufacturing Methods and Technology programs aimed at implementing new developments in production end-item hardware.

However, there is a course of events which most every development takes starting from basic and applied research and progressing through various phases of hardware development (laboratory-scale components, prototype components, full-scale testing, possibly flight testing, and finally implementation).

The Government's policy of supporting IRAD continues to bring many promising hardware developments to the prototype stage. However, much manufacturing development is still required before most promising processes or materials can be applied to actual flight hardware. This gap between early R&D effort and final implementation is partially filled by the MM&T program; however, there are times when an IRAD-supported effort appears promising on a preliminary basis but additional work is needed for verification before an MM&T program can be undertaken. This additional effort can be considered Manufacturing Development (MD) which fits within the general scope of the AVSCOM Manufacturing Technology Program. Once the MD program is completed (presumably with success), a corresponding MM&T program can be undertaken to qualify the optimum process for full-scale testing and possibly flight testing.

Figure 1 is a general schematic of the development of new manufacturing technologies from the idea stage to implementation in production. As the figure shows, a large number of identified problems proceed through the R&D stage where some are screened out as not being practical or achievable. Some then pass onto the MD stage where prototype testing can take

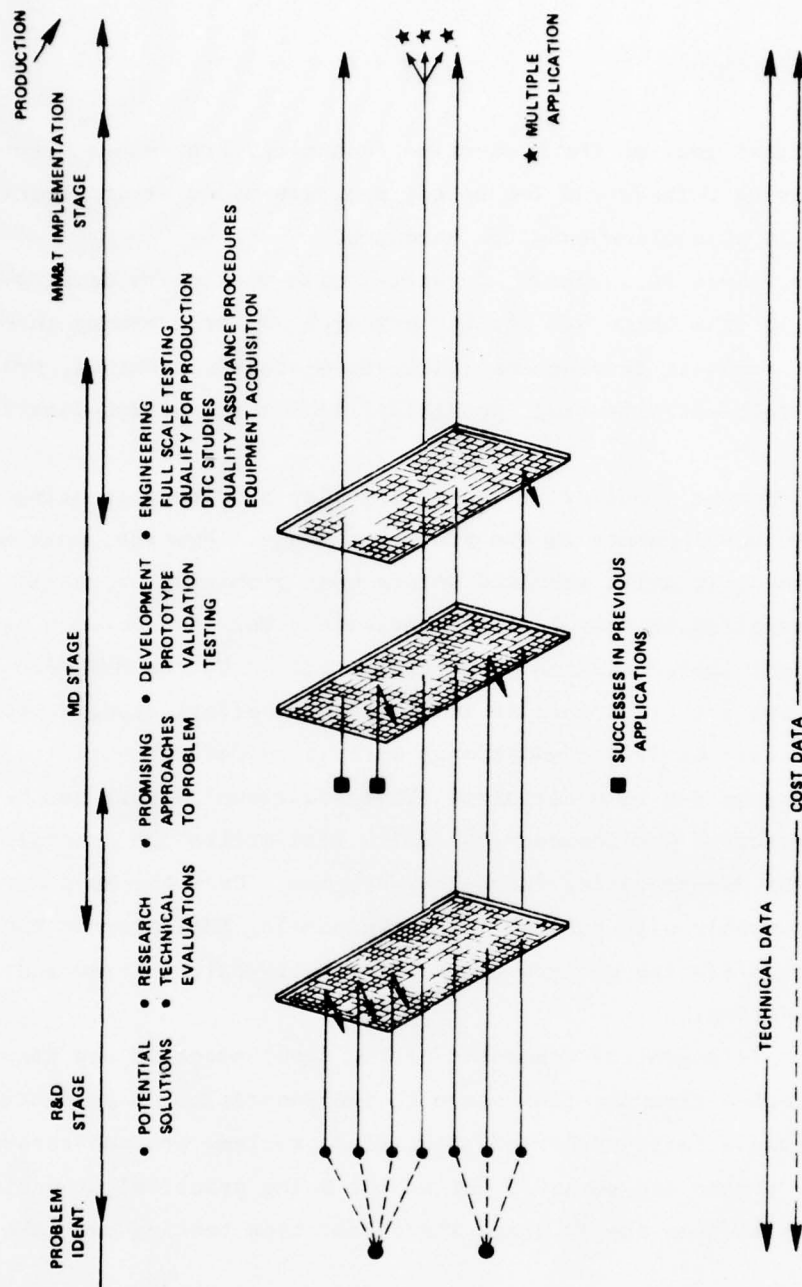


FIGURE 1. EVOLUTION OF NEW MANUFACTURING TECHNOLOGIES

place as the potential solution begins to develop. Finally, those that survive the second stage move into the MM&T implementation stage where full scale testing takes place and the new technique or component is qualified for production. As indicated on the bottom of the figure, technical data is being gathered throughout this development period with cost data hopefully beginning to emerge as the effort moves into the MD stage.

On the assumption that AVSCOM can justify a suitable manufacturing technology budget, it is our opinion that the policy of AVSCOM should be modified to include projects which are more manufacturing development in nature in addition to the end-item related projects now being planned. Such a policy modification would probably be based on the provision that the MD projects have a reasonably well-defined follow-on MM&T phase aimed at implementing the new processes or materials in specific end-items. However, it will be important to spell out in advance the qualification steps necessary to incorporate the advanced process or material, including bench testing and possibly flight testing. The AVSCOM appropriation should, therefore, include sufficient funding for supporting some, if not all, of the qualification steps.

During the course of this study, the Battelle staff identified nearly 40 percent of the potential projects as fitting more in an MD category than in MM&T. This represents over 100 potential projects which are more accurately classified as Manufacturing Development.

Manufacturing Technology for Developmental Systems

A typical comment brought out during the interviews with industry might be paraphrased as follows:

"It is appropriate for AVSCOM to initiate projects related to ongoing production buys, but why don't they also initiate projects which will make sure that

production techniques are available at the time when production buys begin (on helicopters now under development such as UTTAS and AAH)".

A phase in the development of Army weapon systems is Producibility Engineering and Planning (PEP), wherein a realistic plan for production is developed. During the development of this plan, decisions must be made as to whether new manufacturing techniques are far enough along in development to apply or if techniques used in the past must be utilized. However, were funds available, new manufacturing developments related specifically to the future production of an individual system could be demonstrated, proved out and incorporated in the production plan so that the technology would be available at the time production buys begin. Although it is understood that some limited manufacturing technology funding can be made available, such efforts are apparently minimal on the UTTAS and AAH system developments.

Of course, some of these type efforts have been funded, such as:

- Automated tape layup of rotor components (Boeing-
- Automated multispindle machine for producing blisks (General Electric).

However, it is our recommendation that AVSCOM increase its efforts in this area, primarily to benefit future system developments.

Technical Guidelines

It is reasonably clear that the practice of soliciting all kinds of project ideas over a virtually unlimited scope of potential project areas ends up with a tremendously large task of sorting out those projects which might have the greatest potential payoff in return on Army investments and, which qualify for MM&T funding. This practice seems to have two predominant reactions from industrial firms, which either:

- Submit long shopping lists of potential projects, or
- Don't bother to submit ideas.

In addition it is evident that responding mainly to "bottom-up" project submissions from many firms does not provide for the development of a cohesive, proactive plan of Manufacturing Technology action designed to develop longer-ranging solutions to longer-ranging goals. Reaction and responsiveness to industry needs, of course, is important but can lead to a somewhat fragmented Manufacturing Technology plan. On the other hand, for AVSCOM to have a formal "top-down" plan established without regard to industry needs and ideas would be completely nonresponsive.

It is believed important for AVSCOM to combine the "top-down" and "bottom-up" approaches in a technical guidance plan including project areas or "thrusts" where AVSCOM initiates actions and where each accomplishment can complement the next within a given "thrust" area. However, the level of effort within the technical guidance is highly dependent upon the size of the Manufacturing Technology budget.

Giving consideration to the following:

- That most projects should be aimed beyond demonstration to the point of implementation, and
- That such projects will require funding for flight testing in addition to bench testing, thus will often cost about twice as much to complete as the typical projects of the past.

It is foreseeable that the budget for Aviation Manufacturing Technology should increase substantially. For example, a two-fold increase in the number of MM&T projects coupled with a two-fold increase in the budgets for each project would represent a four-fold increase in the annual Manufacturing Technology budget.

Considering that the UTTAS and AAH helicopters will be reaching the production stages during the next two years and that there will be an obvious need for production technology support, an annual budget of about 10 million dollars seems appropriate.

However, if AVSCOM's annual Manufacturing Technology budget were limited to less than \$5 million, it would seem more appropriate to limit the subject areas so that the staff of the Production Technology Branch can spend more time in managing its ongoing efforts.

For example, a limited effort might have more impact if some of the following changes were made in the scope:

- (1) Delete transmission gears, shafts, and seals but concentrate on the housings .
- (2) Drop compressor components of turbine engines but concentrate efforts on the turbine components .
- (3) Exclude virtually all airframe components and concentrate on reducing the high labor cost of joining and inspecting airframes.
- (4) Drop rotor mast/head components but concentrate on rotor blades (main and tail).

This approach would help the AVSCOM staff in concentrating its effort on a smaller number of project submissions from industry and would alert industry to submit project suggestions which fall within a narrower scope. Hopefully, industry would also respond with more detailed appraisals of potential return on investment for each project submitted.

Another way that AVSCOM could handle limited Manufacturing Technology funding is to concentrate its efforts to support the carry on of developments which have already been demonstrated feasible on IRAD programs. Furthermore, such projects could be confined to those efforts where the potential contractor would have made a carefully presented cost-benefit analysis.

Either or both of these policies would substantially reduce the number of unsupported project submissions. However, the latter approach could lead to sole-source procurements in most cases. This then becomes a matter for Army policy to determine whether sole-source procurement for a project

aimed at implementing a new process into a specific end-item is in the best interest of the Government. We believe it would be a proper policy for a production-support group like the Production Technology Branch.

On the assumption that AVSCOM's Production Technology Branch can justify an annual budget more in line with the \$10 million figure, and this seems more appropriate considering the many projects needed to support the AAH and UTTAS programs during the coming five-year period, it is our opinion that the recommendations described within the Aviation Manufacturing Technology Program -- Technical Guidance section of this report establish a good basis for providing technical guidelines to contractors.

Once the technical guidance is established, however, the contractors still should realize how their submissions will be evaluated in relation to that guidance.

Hopefully, the rating system used in the course of this program will provide a baseline for future utilization by AVSCOM in evaluating suggested programs. Since it is reasonable to assume that the majority of projects which will be submitted, at least in the foreseeable future, will continue to be non-MM&T types according to the definitions characterized in this report, it is recommended that AVSCOM further refine a project evaluation system which will provide guidelines to the contractors on the types of projects which can be funded. Table 1 contains some suggested evaluation questions which should be included as part of any overall evaluation procedure ultimately developed in assessing such programs in the future.

ANALYSIS OF MANUFACTURING TECHNOLOGY PROGRAM FUNDING LEAD TIME

Many company representatives contacted in this program were critical of the long incubation period between the time when problems were identified and projects are ultimately initiated. In many cases, it may

TABLE 1. SOME RECOMMENDED EVALUATION QUESTIONS
ABOUT SUGGESTED MM&T PROJECTS

Does the Proposed Project Impact a Current End Item or Items?

Does the Proposed Project Relate to an End Item of the Near Future?

Is it Within a Major Thrust Area?

Will the Results Apply to More Than One System? What Systems?

Does the Source of the Suggestion Provide Reasonably Well Documented
Data to Demonstrate a Significant Cost Reduction?

Would the Project Meet a Unique Military Requirement?

Is the Project Needed to Make an Informed Decision?

Will the Project Lead to Improved Performance?

Will the Project Lead to Reduced Weight?

Does the State of Art Really Need Advancement for Application to Helicopters?

Will the Proposed Project Advance the State of Art to the Point of
Implementation?

be 3 years before these programs begin. As a result, urgent production problems are either not submitted for Army funding and are carried out by individual companies with IRAD funds or are not resolved in time for production buys.

Further, private companies can be hesitant in submitting proposed projects to the Army if non-disclosure of the impending manufacturing development could also place the company in a stronger market position. This type of manufacturing technology development is more often continued fully by industry or partially with IRAD funding.

Thus, contractors and subcontractors have a built-in incentive for submitting to AVSCOM (or to any Government Agency) those problems which are likely to have long-term, nonproprietary solutions.

It is our recommendation that an Accelerated Implementation approach be initiated to allow a quick response to urgent quality or performance problems which are being encountered, either in operating vehicles or those approaching the production stage and to follow up on promising IRAD programs in a timely manner.

Figure 2 shows how Accelerated Implementation of new technology can impact on the potential dollar payback or return on investment for one aircraft system and, with appropriate technology transfer, could show even greater savings if applicable to a second aircraft system. In contrast, the dashed lines in Figure 2 show the delays which occur in obtaining return on investment when implementation does not take place for 3 years or more.

Giving consideration to the foregoing discussion, it is recommended that AVSCOM establish part of its Manufacturing Technology program such that at least 20 percent of each technology area is tentatively funded to assure implementation in specific end item aircraft on an accelerated basis.

We would recommend beginning this type of effort with a small number of highly promising projects. A low success rate could mean dropping the Accelerated Implementation approach. A high success rate should

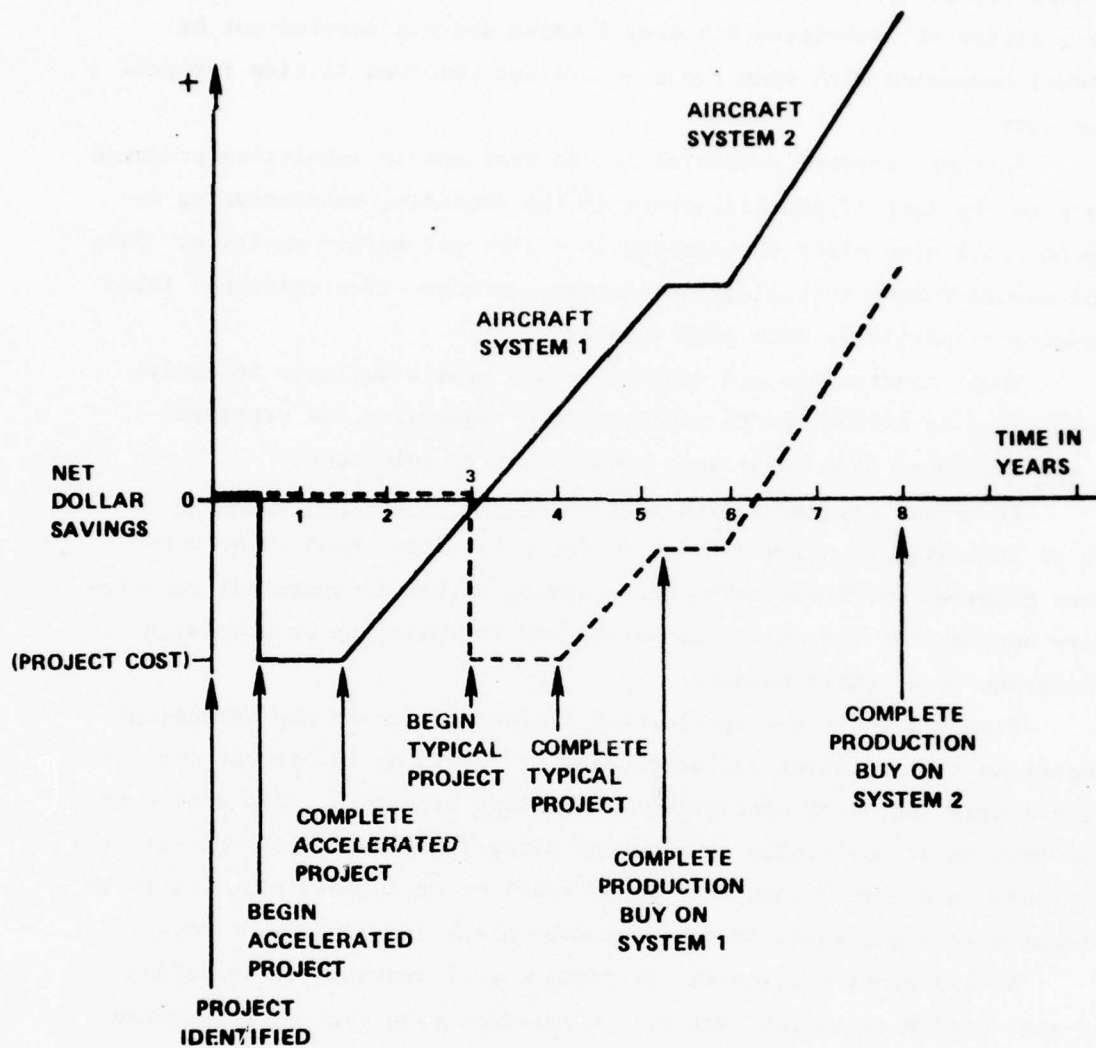


FIGURE 2. VALUE OF ACCELERATED IMPLEMENTATION PROJECTS
IN INCREASING DOLLAR SAVINGS

encourage the Army to proceed with such a program on a broader scale, gaining both increased payoff and improved cooperation with the industrial firms which up to now have had a generally unfavorable feeling about the responsiveness of the AVSCOM program.

Figure 3 shows the stages that could be visualized in using IRAD funding to identify problem areas and evaluate potential solutions. If unsuccessful, work would then stop; if promising, then a highly concentrated effort though MD funds could bring the development to a point for full-scale testing, followed by MM&T funding to qualify and test the development prior to implementation and production. We believe this philosophy is extremely important in the ultimate implementation of Manufacturing Technology programs supported by AVSCOM and should prove successful in providing good dollar paybacks and return on investments through the use of Accelerated Implementation.

ANALYSIS OF MANUFACTURING TECHNOLOGY PROGRAM IMPLEMENTATION

General

There are times when it can be important to support projects aimed at requalifying processes/materials in an existing end item to gain sufficient experience to apply the processes/materials to a newer end item. The immediate cost benefit of this approach is often obscure for the older aircraft. However, the confidence gained and the eventual application in the newer aircraft should more than justify taking such actions. A case in point is the application of hot isostatic processing to the current cast blades being used in the T53 and T55 engines at Lycoming. Hot isostatic processing has been responsible for a substantial reduction in the scrap rate of cast turbine blades and vanes. It is understandable that General Electric could extend the application of the process to other components such as turbine disks used on the T-700.

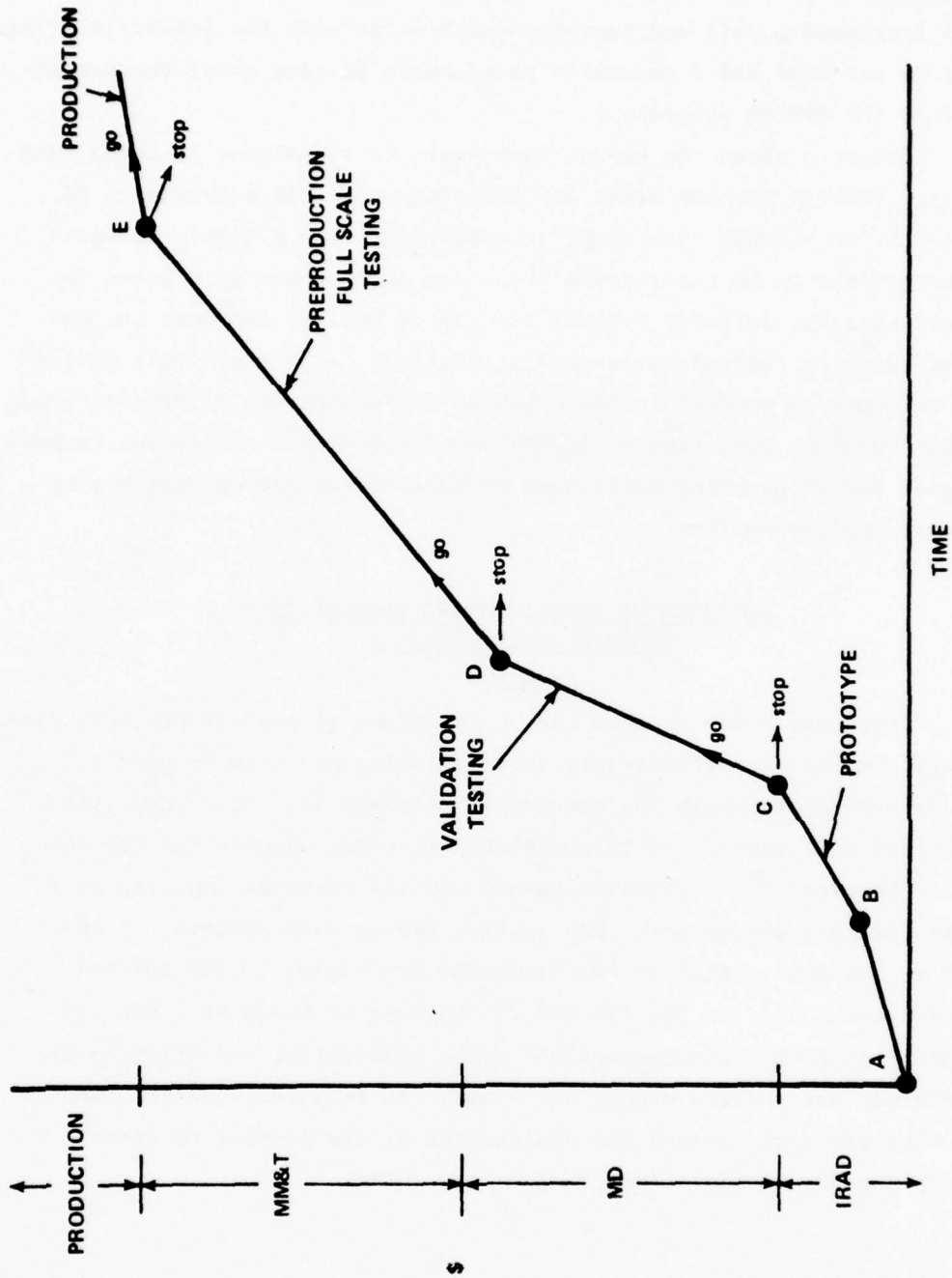


FIGURE 3. VALUE OF ACCELERATED IMPLEMENTATION PROGRAM IN MOVING NEW TECHNOLOGY INTO PRODUCTION

However, it should be recognized that there is an inherent tendency for a firm not to quickly adopt a newly introduced development made by another firm. Some have compared this to the not-invented-here attitude, but a new gear material used in a given transmission may not always be best in the next or a joining technique used at one company may not fit in with the tooling requirements at another. Furthermore, design and stress data requirements may be different enough that the new product or process cannot be adopted on all helicopters. In any case, the Army should not feel disappointed that all companies do not adopt the new technology in their respective aircraft. On the other hand, it is not unreasonable for AVSCOM to expect that a large portion of its MM&T program reaches implementation in production aircraft. To achieve this goal, use can be made of project reports and presentations as well as including implementation as an integral part of each MM&T project.

Project Reports

Interviews with representatives of most firms contacted indicated that the majority of their engineering staff does not have the chance to review the majority of reports resulting from the MM&T programs supported by the Army. When asked for some of the reasons for this, the discussion usually turned to the fact that there are over 100 engineers at most of the prime contractors who could consider adopting the report findings. The chance of this happening is remote in many cases because the report may end up on a shelf without suitable cross-indexing to help someone find it. As an example of what can be done, General Electric distributes summaries of Government reports to all of its design engineers so that the chances for application are much greater. However, as far as Army policy is concerned, it could prove to be a good investment to issue additional copies of the reports so that there is an improved incentive for the recipient to circulate the other copies.

We recommend that AVSCOM conduct a brief survey of some of the suppliers of aircraft to determine the most suitable quantity of reports to be distributed per company and to identify those key persons with the greatest opportunity to impact the incorporation of the results. This approach should insure that the project findings have the best chance for finding broader applications.

The publication of monthly periodicals in the form of abstracts and journals, which is being discussed by the staffs of PEQUA and DARCOM, represents a good start toward the goal of getting other commands and industry briefed on Army R&D and MM&T activities. The forthcoming Manufacturing Technology Management Information System developed by PEQUA and AMMRC will be applicable here also.

Project Presentations

While there seems to be general agreement that project briefings are worthwhile to get project results into the hands of other firms, there was some apprehension expressed for the potential accessibility to proprietary information if the briefings are to be held on-site. The more widely held view was that briefing films or slide presentations would serve the purpose better. In all cases there was agreement that some visual form of transferring the technology was better than the reports alone.

There was some tacit agreement that contractors conducting MM&T projects which are follow-ons to their own company-sponsored or IRAD work should be willing to have a more open-door policy concerning the specific project, perhaps holding an industry briefing about one or two months after completion of the demonstration phase and again after the implementation phase. This kind of contract stipulation could help lessen the concern of those who have strong negative feelings about sole-source contracts.

Clearly, the contractors on such programs would be careful to select those projects which should bear up under the scrutiny of representatives from other contractors.

Assuming that the AVSCOM Manufacturing Technology program receives a reasonably large budget for the coming years, it will be worthwhile to hold periodic seminars either at AVSCOM or elsewhere as appropriate. Such meetings could be planned for on a bi-annual basis somewhat like the seminars held by the Air Force. We understand such meetings are being planned tentatively and fully endorse such an effort.

It has been our experience that holding project briefings and participating in seminars can add about 5 percent to the cost of a \$200,000 project. It is a worthwhile investment in the majority of cases.

Funding of Project Implementation

Too often past programs have left implementation up to the contractor; if the contractor had implemented the technology, a cost reduction would probably not have been realized until well into the procurement contract. The prime factor here is that industry is usually seeking a reasonably short term return on its investment rather than a ROI over the total contract. The fact that most Army procurements are in stepped quantities rather than long term financial commitments helps to deter industry from adopting promising developments.

However, knowledge that AVSCOM could also fund the implementation phases should provide manufacturers with added incentive to continually incorporate advanced developments in the current aircraft. Of course there will be some projects which should be discontinued after the demonstration phase because the hoped for payoffs do not always materialize. On the other hand, the project may prove to be worth continuing if an improvement is demonstrated. The situation would require careful

scrutiny before initiating an implementation phase. It is our opinion that in order to insure a high percentage of project implementation, the AVSCOM appropriation should include funding to support some (if not all) of the qualification steps.

In some cases, it may also be worthwhile to support an effort at a second firm aimed specifically at implementation in order to take full advantage of the cost reduction potential. This could involve requalification of a second system, but if the cost pay-off is worth it, support of a second effort should not be ruled out.

RECOMMENDED FUTURE MANUFACTURING TECHNOLOGY
PROGRAM OPERATION

Returning to the goals of the Production Technology Branch, it is well to review them in light of the foregoing recommendations. It is proposed that future goals of the Production Technology Branch be aimed at:

- (1) Reducing manufacturing costs - Addition of Accelerated Implementation procedures should begin to show return on Army investment within 2 to 3 years.
- (2) Solving problems with reasonable commonality - This goal should remain unchanged, except with funds specifically earmarked as manufacturing technology for developmental aircraft.
- (3) Improve maintainability/reliability of current systems - Adaption of the Accelerated Implementation procedures should provide AVSCOM with greater responsiveness to field problems - especially those requiring an accelerated program aimed at improving service life of components or subcomponents.
- (4) Assuring that production-ready equipment and facilities are ready the time of production buys - This is an area which will require continuing study by the staff at AVSCOM. Development of low-cost composite structures will depend heavily on equipment/facilities which delete much of the currently high labor content. Furthermore, the potential cost benefits of rivet-bonding, precision forging, and many other processes requiring high tooling costs cannot be fully realized without a driving force of actions initiated by AVSCOM.

- (5) Implementing the results of promising IRAD efforts - This goal is sometimes rather elusive because of the potential "sole-source" nature of the projects. It is believed that the Accelerated Implementation effort described will help justify support of such projects - especially those having the greatest potential for return on investment.
- (6) Applying CAD/CAM where cost effective in design, manufacture and/or inspection - This goal remains quite appropriate.
- (7) Enabling informed decisions or choices to be made between candidate materials, processes, equipment and/or designs - AVSCOM could step up its action of supporting detailed studies aimed at assessing candidate processes and/or materials. These could be initiated by AVSCOM with possible assistance by AMRDL or AMMRC.
- (8) Getting the results of timely MD and MM&T projects into the hands of operating personnel who can apply the technologies where cost effective in Army systems - This goal is of vital importance and can be approached by any or all of the ways described previously under Analysis of Manufacturing Technology Program Implementation.

A question is raised about whether or not AVSCOM should support projects which are somewhat speculative in nature but where the cost benefits could be high. It is believed that AVSCOM should initiate such projects only if there is sufficient data/experience available from IRAD efforts to give reasonable confidence in the outcome. Such evidence should be made available to AVSCOM before initiating such projects which fit most appropriately under goal number (5).

AVIATION MANUFACTURING TECHNOLOGY PROGRAM - TECHNICAL GUIDANCE

GENERAL

In the development of recommended Technical Guidance for the AVSCOM Manufacturing Technology Program, two general approaches were considered:

- "Top-Down Approach". It is possible to determine factors which "drive" the costs of manufacturing and/or operating helicopters and to therefore determine areas where funding of manufacturing technology programs would have the greatest impact.
- "Bottom-Up Approach". It is also possible to obtain input in the form of suggested projects and to therefore determine areas where the actual manufacturers and/or operators feel manufacturing technology programs are needed.

However, there are inherent weaknesses in either approach. It is necessary to obtain input from the manufacturers and/or operators to define potential actions to attack the cost drivers defined by the "top-down" approach. On the other hand, it is necessary to temper the project ideas of the "bottom-up" approach with knowledge of the overall effects that such projects can have on the manufacture and/or operation.

Recognizing the drawbacks of unilaterally using either identified approach, the optimum method to develop a realistic technical guidance plan appears to be a combination of the two approaches. Consequently, the following major tasks were undertaken:

- (1) Identification and analysis of cost drivers ("top-down")

- (2) Identification and evaluation of manufacturing technology project suggestions ("bottom-up")
- (3) Formulation of technical guidance based on combination of (1) and (2).

As the first step, major cost drivers which affect helicopter manufacture were examined, with particular emphasis on identifying those areas capable of being affected by application of new manufacturing technologies. Furthermore, this step provided an information base upon which the assessment of project suggestions conducted in step two could be examined.

The basic input for the second step consisted of some 278 suggested projects which were provided through contacts and discussions with helicopter prime and component manufactures and by AVSCOM, as well as other Government organizations.

A system for evaluating the project suggestions was devised covering rating criteria, plus calculations (where possible) on the return on investment which might be realized if selected programs were investigated and proved to be successful and implementable. Also tied into these project evaluations was the state of development of the suggested project, whether it was ready for MM&T funding or was in the early or middle stages of development and required further basic funding before being ready for evaluation as an MM&T project.

Based on the cost driver input and the evaluations made of individual projects, 12 major recommended thrusts by technological area were defined. Those technical thrusts considered important for each helicopter subsystem (airframe, engine, rotor, drive) were presented; and a 5-year technical guidance plan was developed, which indicates recommended technical areas, extent of funding and the estimated timing for action between FY-77 and FY-82, as well as indicating where manufacturing development money should be spent either prior to or in conjunction with MM&T funding.

In the sections which follow, the work conducted in each of the three task areas is described.

COST DRIVERS AFFECTING HELICOPTER MANUFACTURE

General

Design-to-Cost programs have become increasingly important and integral parts of recent DoD acquisitions of virtually all military hardware from relatively simple ballistic components to the most sophisticated systems. The objectives of the DoD have changed from placing the overriding emphasis on improved performance to an emphasis on quality equipment having acceptable performance for an affordable cost.

Some might interpret this change in philosophy as being responsible for putting low cost ahead of performance as a goal, but the key phrase is worth repeating -- acceptable performance at affordable cost.

What are the cost drivers affecting the manufacture of helicopters? It is easy to generalize about such factors as high labor, high cost materials, high part counts, etc. But it is important to be more specific. Perhaps starting out with a base-line helicopter designed for civilian use is an effective way of assessing cost drivers.

Bell Helicopter Company and its licensees have delivered more than 3500 of its Jetranger helicopters to both private firms and Governments throughout the world by mid-1974.* In 1968, Bell began the design and manufacture of the OH58, which is similar in many respects to the Jetranger. However, a number of changes were required to adapt the basic aircraft to more hostile environments; these changes included:

- Mechanical controls (less vulnerable to ballistic damage than hydraulics)
- Addition of defensive armament (7.62 mm mini gun)
- Faster rate of climb (larger rotors)
- Redundant electrical circuitries (reduce ballistic vulnerability) among other changes.

* Jane's All the World Aircraft - 1974.

The Jetranger is designed by Bell with its own specifications and the company is relatively free to make unilateral changes in the commercial version - changes to increase performance or to reduce costs. By contrast, any changes that Bell (or any contractor) sees as important for reducing costs and/or improving performance of Army helicopters must be cleared through the program office at AVSCOM in the form of contract modifications.

Furthermore, the quantities of helicopters under contract at any one time are relatively low, giving the contractor little opportunity to partially build airframes in advance of anticipated orders. It is entirely possible and often likely for the Army to plan for the purchase of quantities on the order of several hundred aircraft over an 8- to 10-year period. However, the actual production releases often represent only a fraction of this and only for a 1- or 2-year period. Thus (unless there is a mobilization effort) the helicopter manufacturer is not likely to invest in production-ready tooling because there is always some doubt about whether there will be drastic changes in mission requirements making the current model obsolete.

By contrast, the commercial versions can most always be sold. For example, the commercial sales of the jet-prop Lockheed Electra to foreign countries continued well after the aircraft became obsolete in domestic airline use.

Thus, requirements unique to military environments have a tremendous influence on helicopter cost. As another example, armament and other unique military functions of the AAH add up to nearly 45 percent of the direct labor and material costs and the AH-1 (Cobra) helicopter armament adds up to 30 percent of such costs.*.

* "Manufacturing Technology Guidance for Army Helicopters", Robert D. French, AMMRC SP 75-8, October 1975.

Helicopter Cost Distribution

Consider again the Cobra helicopter. Following is a percentage distribution of direct labor and material production costs for a variety of subsystems and components on the Cobra*:

<u>Airframe, %</u>	<u>Rotor/Drive, %</u>	<u>Engine, %</u>
Fuselage/landing gear	Drive	Compressor
Tail boom and fin	Rotor/Wings	Combustor
Hydraulic		Turbine
Electrical, Inst.		Exhaust Diffuser
Flight Controls		Drive Gearing
Armament		Miscellaneous

By contrast, the costs of producing a commercial helicopter of reasonably similar design are substantially lower and the cost distributions by percentage are significantly different. It is estimated that the approximate cost distributions for a commercial helicopter reasonably similar to the Cobra is as follows:

<u>Airframe, %</u>	<u>Rotor/Drive, %</u>	<u>Engine, %</u>
28.8 Fuselage/landing gear	9.9 Rotor/Wings	4.8 Compressor
2.3 Tail Boom	9.3 Rotor Assembly	1.0 Combustor
7.5 Hydraulic System	6.8 Drive	4.0 Turbine
11.6 Hydraulic System		0.7 Exhaust Diffuser
2.5 Controls		3.2 Acc. Drive/Power
0.8 Furnishings		0.5 Miscellaneous
6.3 Integration/Assembly .		Hardware

The percentage differences between the military and the commercial helicopters are primarily due to the fact that the armament (which added up to 30 percent of the military version) is not on the commercial helicopter and thus does not add to the cost base.

* "Manufacturing Technology Guidance for Army Helicopters", Robert D. French, AMMRC SP 75-8, October 1975.

However, the most pronounced difference noted when comparing cost percentages between the two helicopters is in the fuselage construction. On appearance, the costs for providing eye appeal, passenger comfort and other accessory appointments are the contributing factors to the higher percentages for the commercial aircraft fuselage. On the other hand, some of the structural costs for supporting armor and armament could actually be considered part of the fuselage costs in the military helicopter.

The point of this discussion is that such comparisons of cost distributions for purpose of identifying specific cost drivers have to be considered as having marginal accuracy.

Distribution of helicopter costs are available in the literature*; however, the analysis of the distributions in trying to identify cost drivers can be quite involved and the results not overly useful in deciding where the emphasis in a manufacturing technology program should be placed. Likewise, identification of high cost areas is useful only if the high costs can be affected by manufacturing technology emphasis; it is the identification of these types of costs which is essential.

Helicopter Cost Variability

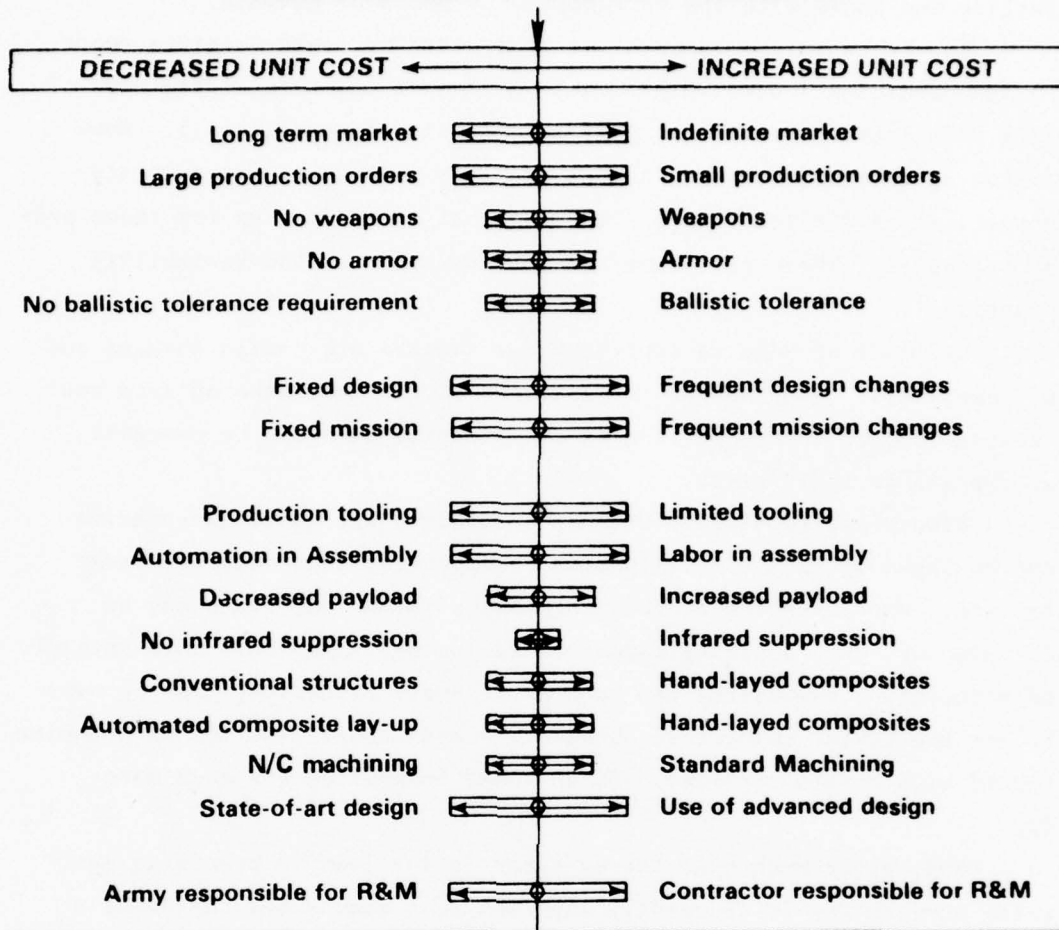
Considering helicopter production costs, it is instructive to review Figure 4, which indicates baseline costs for a fictitious helicopter purchased in production quantities over a period of several years. In the figure, several examples of factors which influence production costs are compared in a general way. These factors can also be looked upon as production cost drivers, with variable degrees of effect on cost.

* "Manufacturing Technology Guidance for Army Helicopters", Robert D. French, AMMRC SP 75-8, October 1975.

"Army Helicopter Cost Drivers", Harold K. Reddick, Jr., Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, USAAMRDL-TM-7, August 1975.

"Turbine Engine and Turbine Engine Component Cost", David B. Cale, U. S. Army Aviation Materiel Laboratories, USAAVLABS Technical Report 68-59, July 1968.

PRODUCTION COST OF BASELINE HELICOPTER



Cost Influence:

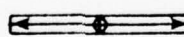


-  — Major Influence on Costs (High variability)
-  — Intermediate Influence
-  — Minor Influence on Costs (Low variability)

FIGURE 4. SOME EXAMPLES OF FACTORS INFLUENCING PRODUCTION COST OF HELICOPTERS

It is helpful to distinguish between those cost factors with high variability and those with low variability by means of example.

For instance, parts machined from plate or rough forgings represent large machining losses which, in turn, causes one to evaluate ways of reducing chip losses (precision casting, precision forging, etc.). However, knowing that only a small number of parts will be required in any given year, it is difficult to justify the cost of tooling up for these precision processes. These processes are good examples of low-variability cost factors.

Examples of high variability cost factors are design changes and use of composites. Many design changes have little influence on cost but some design changes in one portion of a helicopter can lead to cascaded design changes in other areas.

Fiberglass reinforced organic composites are quite inexpensive and can be layed up into a variety of curved panels, door hatches, radar covers, etc. Many examples of such composites in use for years can be cited. However, when applying composite technology to produce more severely loaded structures, composites can become extremely expensive, costing over \$30/lb for the Kevlar reinforced epoxies and over \$50/lb for the HS graphite reinforced high modulus epoxies. Boron-epoxy composites are even more costly.

And, since much hand lay-up labor is involved in preparing most composite structures, it is readily apparent that composites represent a high variability cost factor.

The high variability cost factors require first attention in choosing what costs to attack by means of manufacturing technology projects.

The task of identifying high variability cost factors throughout the helicopter system is not straightforward. For example, the Air Force Manufacturing Technology Division holds workshops aimed at identifying the

key cost drivers in the manufacture of aircraft*. From their findings, a variation of anywhere from 30 percent to 70 percent of the total manufacturing costs are attributable to subassembly and assembly man-hours and that a good part of the variation is attributable to the degree automation is used. Other important (high variability) cost drivers include:

- Chip removal (and metal wastage)
- Manual, and frequently redundant, quality-control operations
- Tooling costs
- Too many preassembly components (not enough modularization)
- Too many fasteners of too many shapes and sizes.

Marchinski of Boeing-Vertol^(*) indicates that labor represents the following approximate percent of recurring production costs for different helicopter subsystems:

Landing Gear	50%
Drive	65%
Rotor	50%
Fuselage	88%
Nonstructural Subsystems and Installation.	45%

While labor accounts for over 50 percent of the body group (excluding engines, armament), methods for substantially reducing assembly labor have not been overly successful without making drastic changes in the number of parts being assembled (i.e., high part counts require high labor costs).

* "Summary of Air Force/Industry Manufacturing Cost Reduction Study", Technical Memorandum AFML-TM-LT-73-1 (January, 1973) (Proprietary).

(*) Marchinski, L. J., "Design to Cost at Work for Helicopter Systems", AIAA Paper No. 74-962, presented at 6th Aircraft Design Flight Test and Operations Meeting, Los Angeles, California, August, 1974.

Field visits with prime contractors have confirmed that the following are key cost driving factors requiring high labor:

- High part count
- High labor in subassembly and assembly
- Tooling
- Repair and maintenance
- Specifications, inspection
- Excess chip removal
- Design
- Use of labor intensive composites (hand lay-up)
- Low production quantities.

This agrees reasonably well with a table included in Marchinski's paper which is reproduced in Table 2. Marchinski identifies material as a cost-driving factor recognizing that this encompasses both expensive materials and the high cost of chip machining which, in turn causes the cost per pound of finished article to increase drastically. But perhaps the most important single production cost driver relates to low production buys.

This seemingly elementary but pertinent observation is important to be kept in mind when evaluating potential cost-reduction studies. As an illustration, one company claims that converting from forgings to castings (or powder-metal preforms) should save the tremendous amount of material wasted while machining a rough forging. Examples are frequently given where the blocker-type forging outline is an inch or more away from the final part contour. Yet this is the type of forging a typical company will produce on a limited tooling budget. By contrast, most forging companies are capable of forging much closer to the finish contour (hence lower material scrap) with a more expensive set of forging dies. This is just not done, however, until the production quantities are in the hundreds; otherwise, there is no way of recovering the more expensive die costs. This also

TABLE 2. COST-DRIVING SUBSYSTEMS

System	Subsystems	Cost-Driving Factors
Airframe	Frame	Number of parts
	Bulkheads	Number of fasteners
	Skin-stringer panels	Material
	Beams	Number of manufacturing operations
Drive system	Gears and bearings	Special processes
	Drive shafts	Tolerances
	Gearboxes	Number of parts
		Number of machine operations
		Specifications
		Reduction factor
		Weight
Rotor group		Horsepower
		Inspection requirements
	Blades	Number of parts
	Hub assembly	Number and type of bearings
	Upper controls	Number of fabrication operations
		Number of finish operations
Flight controls		Material
	Actuators and servos	Number of parts in each category
	Mechanical components	Number of fabrication operations
	Electrical/electronic systems	Tolerances
		Number of mounting points
		Electrical connections

explains why close-tolerance isothermal forging is not extensively practiced. At one company visited, for example, its customer is committed to hot-die isothermal forging. Roughly a full 8-hour shift is required to set up and heat the dies only to forge 10 to 12 turbine disks. Fifty to 100 disks could be forged for little more than twice the costs for making 10 forgings. This is but one example of where reduced final part costs through reducing chip losses (lighter weight forgings) will continue to be an elusive goal - at least until the part quantities increase substantially.

Figure 5 illustrates the well recognized influence of quantity on unit costs. The lower curve represents the long production runs typical of the automotive industry where the production-ready tooling is used to produce many thousands of parts -- the emphasis is on lower unit costs. The upper curve is more typical of the aircraft industry where the emphasis is on low tooling costs. Thus, unit costs for small quantities are on the order of 2 to 4 times the unit costs for parts produced on a high volume basis.

The middle curve represents an area for AVSCOM consideration. It shows that if production-ready tooling is built at an early stage of procurement, the unit costs throughout an entire program can be expected to be lower than when minimum tooling is used. The main problem here is that if most all components were produced with production-ready tooling during the first year of a purchase contract, the total tooling costs could be 3 to 6 times higher than if minimum tooling is used. The cost benefit of the production-ready tooling might not show up for 2 to 4 years.

This same comparison can be extended to the degree with which automation is applied to reduce labor content in manufacturing helicopter components. For example, the Army is planning to purchase about 1100 UTTAS helicopters between 1977 and 1986. Considering that most of the known labor-saving automation methods for reducing costs on a high production

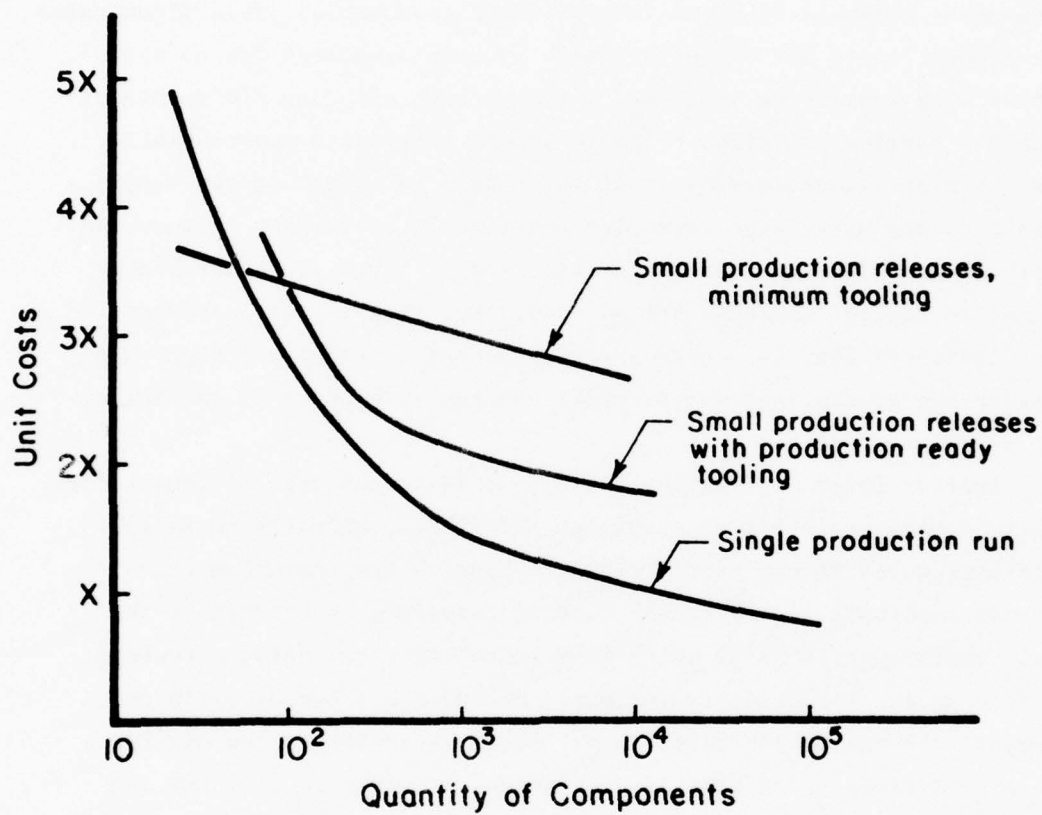


FIGURE 5. RELATIVE INFLUENCE OF PART QUANTITY ON UNIT COSTS (ILLUSTRATION ONLY)

basis were applied at the first year of production, the costs at this early stage would be much higher. Yet, if the Government wants to reduce costs over a total 10-year contract period, it should consider the construction of production-ready tooling and the adoption of labor saving automation wherever practical. Industry is usually in a position to judge where such actions are practical.

The comparison of relative costs for four different methods for producing parts shown in Figure 6 is considered reasonable. This illustrates that the typical costs for producing parts by machining from bar do not change much with increasing quantity. By contrast, adopting N/C machining or closed die forging practices helps to reduce unit costs substantially. Castings are most always lower in cost than the other alternatives until run quantities are quite high where the amortization costs per unit become relatively small. The final costs for critical castings will increase as costly quality control measures are adopted. For example, at least two companies indicated that the costs for testing and eventually scrapping a small percentage of castings for aircraft can run as high as 25 percent of the unit purchase costs.

Another major cost driver identified is in the area of composites. These include many varieties of single-strand fibers, multistrand tapes, and cloth-type woven fibers reinforced with epoxies and thermoplastics.

An important factor in the cost of composite structures is the relatively small quantities in which many ingredients are being purchased nationwide. Again, low quantity purchases of any one fiber or resin or epoxy composition causes increased cost. Since aircraft for the Air Force also use considerable quantities of composites, it might be wise for the Army and Air Force to enter a joint campaign program aimed at standardizing on some of the composite constituents so that a fewer number can be purchased in larger quantities.

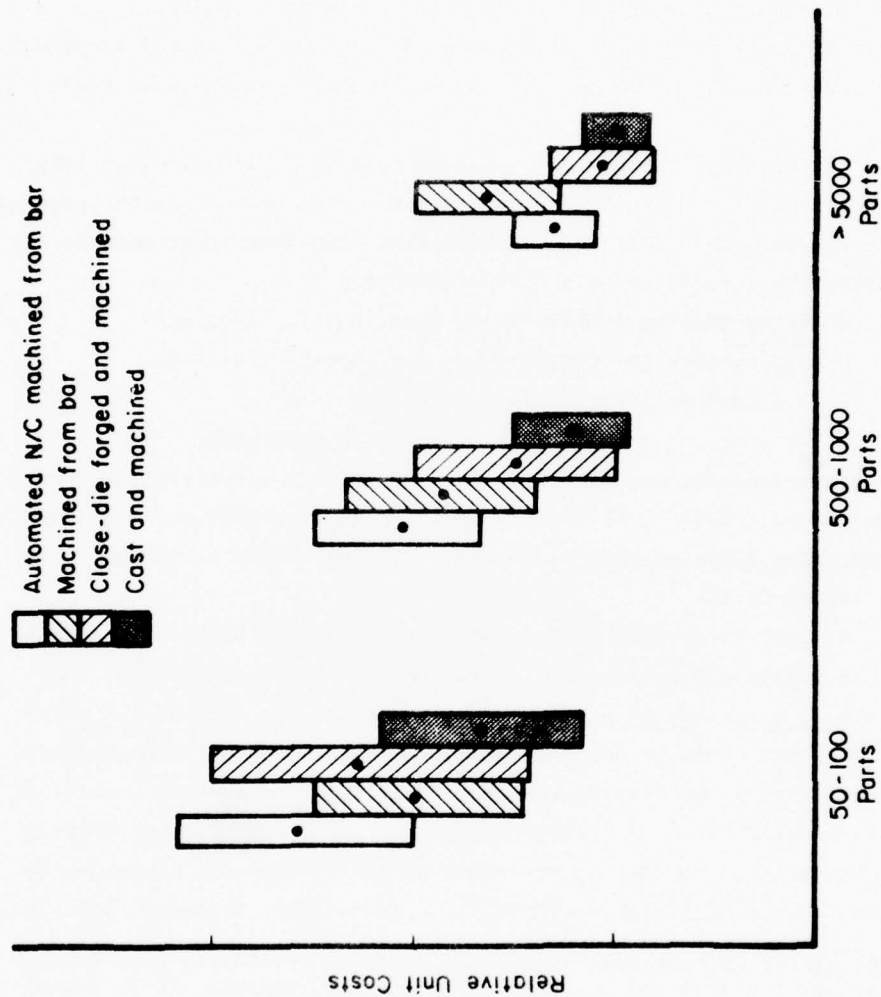


FIGURE 6. TYPICAL COMPARISON OF UNIT COSTS BASED ON QUANTITY

A cost driver specific to composite structures is the tremendous labor content typical for hand-layed up structures. Because blades are produced in larger quantities, fiber winding and tape wrapping machines of various levels of sophistication and control have already been developed either in-house at the helicopter producers or by such independent firms as Fiber Sciences, Advanced Structures, and Goldsworthy Engineering. Continuing development of devices for lay up of airframe structural components could help reduce labor content and provide greater reproducibility of product.

Furthermore, the costs for curing composite structures in large autoclaves represent a significant part of the total costs. In the case of parts having reasonably uniform cross-sections, two lower-cost methods for curing composite structures have been developed:

- Using forming tools with integral heating and cooling systems (electrical, hot oil, and/or live steam followed by internal water cooling)
- Passing the part through a microwave generator.

However, nondestructive methods for detecting uncured or partially-cured areas are needed before these methods reach production status. It is anticipated that more industry-wide development will be needed in the area of reducing curing costs.

A major life cycle cost driver, as opposed to production cost drivers, is repair and maintenance. After helicopters are fielded, they are subject to a variety of problems which can have great impact on total cost to the Army. This is one area where the increased use of composites could return worthy benefits to the Army. For example, over 50 percent of all airframe maintenance is related to fasteners and secondary structures and approximately 50 percent of all rotor blades removed are subsequently scrapped.* By the application of composite technology, fastener reductions

* Army Helicopter Cost Drivers", Harold K. Reddick Jr. Eustis U.S. Army Air Mobility Research and Development Laboratory, USAAMRDL-TM-7, August 1975.

will follow and improved repairability can be anticipated. It is important for AVSCOM to continue identifying future opportunities to attack repair and maintenance problems as they occur.

Examples of cost drivers cited by one company may not necessarily be of major importance to another. At one firm, the cost of precise contour machining of Nomex honeycomb fillers for rotor blades was considered a major contributor to cost because of slow cutting rates and low tool life. Another firm which "grinds" away the honeycomb using an abrasive disk does not identify such machining as a major cost problem, even though dimensional accuracy may be lower than desired. But, such individual problem evaluations are the subject of the next section.

However, before looking at the project suggestions, it is well to repeat some major cost drivers which were identified and, as a result, provide an overall viewpoint of the types of programs which can affect helicopter costs:

- High part count
- High labor in assembly (nonautomation)
- Tooling costs
- Repair and maintenance
- Specifications/inspection
- Chip removal
- Design costs
- Composites
- Low production quantities.

These cost drivers will serve to establish appropriate AVSCOM actions based upon project suggestions to attack the cost drivers.

REVIEW OF MANUFACTURING TECHNOLOGY PROJECT SUGGESTIONS

Identification of Manufacturing Technology Project Suggestions

During this study, extensive discussions were held with prime contractors, engine builders, repair and maintenance facilities, and suppliers of such components as castings, forgings, composite structures, and rotor blades. A list of these information sources appears in Table 3.

More than 275 solutions to identifiable problems were suggested during these discussions; these project suggestions appear in Appendix B. The Battelle staff concentrated on identifying the problems and potential solutions for especially the newer systems (AAH, UTTAS, modifications of CH47, AH-1, etc.). Interviews with key engineering personnel at prime and sub-contractors proved to be the best sources for information.

The project suggestions identified were classified by the four helicopter subsystems:

- Airframe
- Engine
- Rotor
- Drive.

Greatest emphasis was placed on identifying those areas related to manufacture of hardware components, giving least attention to electronics and weaponry.

In some instances, the companies were applying IRAD funding to the task of solving the specific problems. Many of the potential solutions were considered by the contractors to be simply part of their contract in supplying prototype and/or production helicopters. In the majority of cases, the problems brought to the attention of the Battelle staff were those which the contractors felt were important enough that they (the contractors) were submitting

TABLE 3. SOURCES OF INFORMATION

Private Industry

Advanced Structures, Inc. (Monrovia, CA)
Allison Division of General Motors Company (Indianapolis, IN)
Bell Helicopter Textron (Fort Worth, TX)
Boeing-Vertol Company (Morton, PA)
Fiber Sciences, Inc. (Gardena, CA)
General Electric Company (Lynn, MA)
Goldsworthy Engineering, Inc. (Torrance, CA)
Hughes Helicopters (Culver City, CA)
Lycoming Division - AVCO Corporation (Stratford, CT)
Sikorsky Aircraft (Stratford, CT)
TiTech International, Inc. (Pomona, CA)
Wyman Gordon Company (North Grafton, MA)
Hamilton Standard Div of United Technologies (S)

Government

Army Aviation Systems Command Production Technology Branch
Army Aviation Project Manager Offices:

- UTTAS
- AAH
- CH-47 Modernization
- AH-1 Cobra

Corpus Christi Army Depot
Wright Patterson Air Force Base

Meetings

American Helicopter Society 31st Annual Forum (Washington, D.C.)
International Conference on Composites (Philadelphia, PA)
Air Force Briefing on Composite Cost Estimating Manual
(Dayton, OH)
Conference on Advanced Composites (Washington, D.C.)
Interim October 1975 Workshop/Briefing on Battelle Study at
AVSCOM (St. Louis, MO)

to AVSCOM for supplemental support by AVSCOM's Manufacturing Technology activity.

However, free and open discussions at each plant helped to identify a large number of problems which had not been discussed with the AVSCOM staff. These discussions were helpful to the Battelle staff in identifying the relative priorities placed on each problem/project area by each firm.

For example, those problems requiring urgent attention are rarely submitted to AVSCOM for possible support largely because of the 2- or 3-year time space normally required to get projects funded and under way. Furthermore, private companies can be hesitant in submitting a potential solution to a problem if the impending manufacturing development could also place the company in a stronger market position with its line of nonmilitary aircraft. This type of manufacturing development is more often supported fully by industry or partially with IRAD funding.

Thus, contractors and subcontracts have a built-in incentive for submitting to AVSCOM (or to any Government Agency) those problems which are likely to have long-term, nonproprietary solutions. As might be expected, many problems are reasonably common to more than one helicopter system. A few examples of reasonably common, nonproprietary problem areas requiring corresponding longer term solutions include:

- Computer-aided engine rotor balancing systems to reduce balancing costs
- Development of effective nondestructive testing of composite structures to reduce cost of quality assurance
- Infrared suppression of turbine engines and exhaust
- Methods for producing low-cost unitized composite structures for replacing multiple-part metallic structures

- Application of hot isostatic processing to assure quality in close-finish castings (Ti, Ni) and to minimize reliance on high-cost forgings.

Problems unique to individual systems also were identified and evaluated. Examples of such problems and potential solutions include:

- Development of a method for replacing blades on compressor disks having integral blades (blisks)
- Development of high-speed welding methods for brake-formed and seam-welded titanium tubes used for blade spars
- Development of inertia welding for joining shafts to gears which are now assembled with high-cost spline-key arrangements.

The favorable results of some of these many potential projects (if undertaken) could eventually apply to more than one system.

Several manufacturing problems were identified which are unique to the performance of helicopters in hostile environments. Such problems as:

- Infrared suppression of engine exhaust
- Ballistic tolerance of rotor blades, controls
- Crashworthiness of fuselages, and
- Field repairability

were typically cited as reasons for some manufacturing problems not otherwise experienced in helicopter manufacture.

It was considered important to identify those manufacturing technology areas where important progress would lead to improved performance and/or cost effectiveness.

Evaluation of Manufacturing Technology
Project Suggestions

General

Prior to evaluation of the project suggestions, it is well to review Figure 7, which shows a general schematic approach to screening of the over 275 project suggestions which were identified during the course of this program. As previously stated, a large number of identified problems proceed through the R&D stage where some are dropped out as not being practical or achievable. Some then pass onto the Manufacturing Development stage where prototype testing can take place as the potential solution begins to develop. Finally, those that survive the second stage move into the MM&T implementation stage where full scale testing takes place and the new technique or component is qualified for production. As indicated on the bottom of the figure, technical data are being gathered throughout this development period with cost data hopefully beginning to emerge as the effort moves into the Manufacturing Development stage.

The evaluation of suggested projects in this program was accomplished by conducting two types of evaluations:

- (1) State of the art assessment - where does the proposed project rank in the three stages of development through which most successful projects must progress?
- (2) Project rating - what benefit can be derived by conducting the proposed project?

Table 4 is a sample of a data sheet used for the analysis of project suggestions. Problems and potential solutions are listed according to components within each of the four subsystems: airframe, engine, rotor, and drive. On the right side of the table, the state of the art assessment

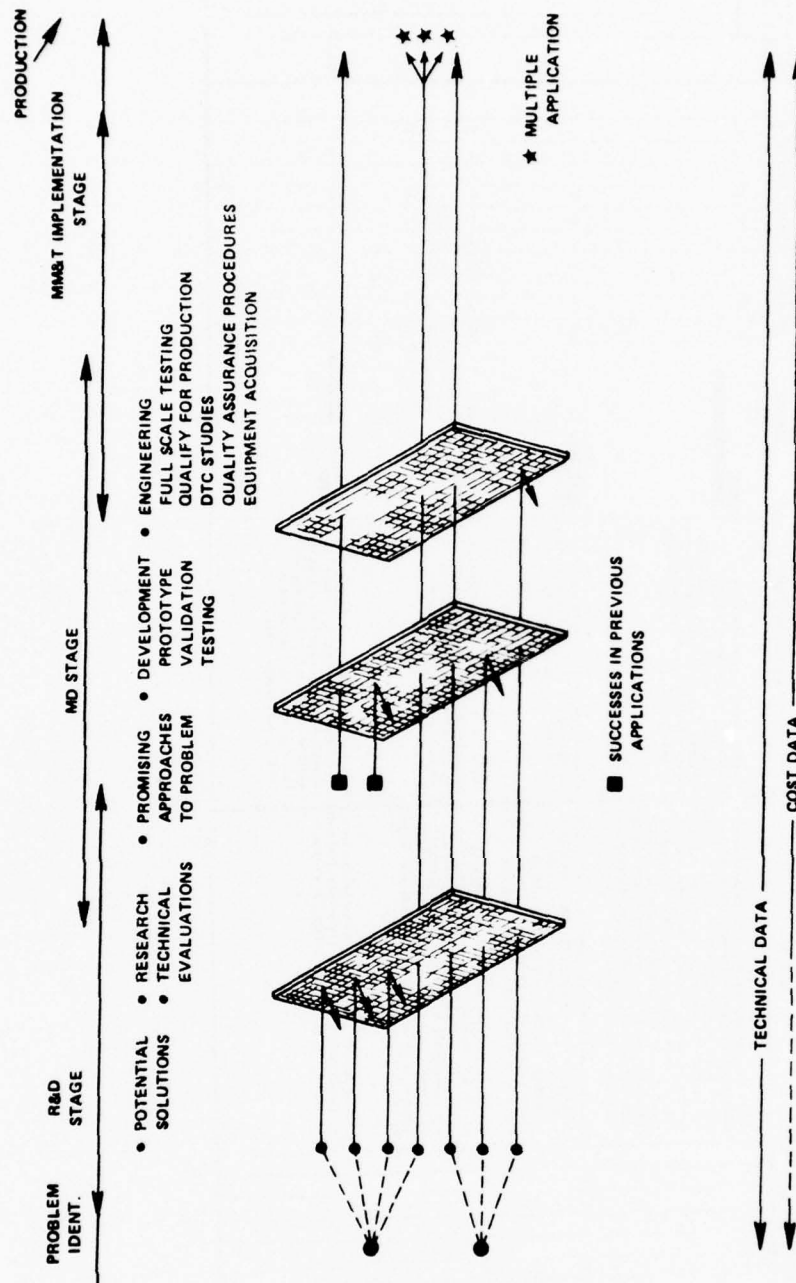


FIGURE 7. EVOLUTION OF NEW MANUFACTURING TECHNOLOGIES

TABLE 4. SAMPLE DATA SHEET USED FOR ANALYSIS OF PROPOSED PROJECTS

CATEGORY	MAJOR THREATS										BATTLE OF PROJECT					SUGGESTED				
TURBINE ENGINES																				
COMPONENT																				
PROBLEM																				
POTENTIAL SOLUTION																				
ADVANTAGES																				
State of Art																				
Cost Reduction																				
Military Adv.																				
Adm.-Sci.-of-Art																				
Improved Reliability																				
Timing																				
Prior 77 78 79 80 81 82																				
Blades	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cone Shaft	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cone Shaft	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Compressor Blades	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Impellers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

is made as well as the rating of the project according to several evaluation criteria. Also on the right side of the table is a proposed time-table for project funding, with an indication also made if manufacturing development is required before MM&T work can be done. All suggested problems were also ultimately grouped in major technical thrust areas which will be discussed in more detail later (these are indicated on the left side of the data sheet). Appendix B includes data sheets for all project suggestions.

Details of the evaluation criteria used are described further below.

Criteria for Evaluation

State-of-the-Art Assessment Criteria

Many project suggestions were considered to be more research in nature than true MM&T efforts aimed at implementing a promising development in end-item aircraft; many other suggestions fell between these extremes. In order to make broad comparisons of the large number of problems, it was considered important to classify the state-of-the-art for each potential project. A series of classifications were defined into which each potential project might fit. These state-of-the-art classifications appear in Table 5.

A brief description of each classification follows:

- I - Implemented in a system. There were a few cases where one company was suggesting work to be done in applying a process/material which has already been applied in another system. In such situations the need for

TABLE 5. STATE-OF-ART CLASSIFICATIONS

State of Art	Classification
Implemented in a system	I
Qualified for production	Q
Flight tested in aircraft	A
Full scale evaluation	B
Prototype evaluation	C
Manufacturing development stage	D
Research and development stage	R
Classification does not apply	--

supplemental MM&T support is questionable at least until good cause can be shown by one firm to adopt a practice already used by another firm.

Q - Qualified for Production. When a process/material is already qualified for production, but not yet implemented, there may be good reasons for applying some supplemental MM&T support especially if the process/material improvement represents a significant cost reduction.

A - Flight tested in aircraft. An innovative design and/or component produced with a new process/material may be flight tested yet not qualified for production or implementation because more experience is required to meet reproducibility requirements. Again, MM&T support could be justified to bring the promising process/material to the implementation stage.

B & C - These classifications represent those where some important work has already been done toward evaluating a process/material, usually as a result of privately supported projects or those conducted under IRAD. These projects fit within the scope of AVSCOM's MM&T effort.

D - Manufacturing development stage. Potential projects within this category are less well defined with respect to end item applications yet can apply to most aircraft. The effort may have involved the preparation of test components for preliminary

evaluation and testing with several potential end items in mind. These projects would be candidates for AVSCOM's MD effort.

R - Research and development stage. Projects reviewed are considered to be at the research stage or projects which seem to fall more in the scopes of AMRDL or AMMRC.

Some project suggestions reviewed were not hardware-oriented yet have varying importance to the AVSCOM MM&T effort. These are left blank in the state-of-the-art category.

Project Rating Criteria

The eight criteria used to define the benefits of and to develop a ranking for each submitted project are listed in Table 6. Four criteria were considered most important and thus are weighted more heavily than the other four criteria. These four were given greater significance because they more directly affect the goals and objectives of the Army in the manufacture of helicopters. Most of the rating criteria are self-explanatory; however, the first (cost reduction) and last (timing) require some discussion.

One of the most important rankings relates to the potential for cost reduction. Specific data were sought from the industry contacts on each project. In some cases, data were furnished which provided a reasonable analysis of cost-benefit. However, in most cases, cost data were supplied only in general terms and specific internally-sensitive cost data were not available. If data presented to the Battelle staff were convincing and the estimated cost reduction potential seemed reasonable corresponding ratings were assigned. In some other cases, the cost reduction potential was estimated by the Battelle staff based on some prior experience within a technical area.

The potential for cost reduction was rated on the basis of a Return on Investment (ROI) ratio, calculated as follows:

<u>Cost of Project</u>	<u>Savings to Army</u>	<u>ROI</u>
X	X	0
	2X	1
	3X	2
	4X	3
	⋮	⋮
	nX	(n-1) X .

For evaluation purposes, expected ROI was rated as shown in Table 6.

TABLE 6. REVIEW SHEET USED FOR RATING A MANUFACTURING TECHNOLOGY
PROJECT SUGGESTION

Rating Criteria	Weighted Scale for Scoring Projects					Score
	2	4	6	8	10	
• Potential for cost reduction Estimated ROI (): (>2)	(>2)	(>3)	(>4)	(>7)	(>10)	
• Application to one or more end item aircraft	2	4	6	8	10	
• Problem unique to military/ combat environment	2	4	6	8	10	
• Project need for improved performance	2	4	6	8	10	
• Project needed to advance state of art to point of implementation or for making an informed decision	1	2	3	4	5	
• Project needed for improved repairability/maintainability	1	2	3	4	5	
• Needed for production-ready tooling to help reduce recurring costs	1	2	3	4	5	
• Timing Months () for needed results: (>48)	1 (>48)	2 (36)	3 (24)	4 (18)	5 (>12)	
Total Score						

The last item, involving the timing (or months required to accomplish the project), bears special note as some of the problems identified require immediate attention where critical tests or experiments must be performed to resolve an unexpected problem in manufacturing or quality control. This type of project points up the need for flexibility in AVSCOM to accommodate some accelerated implementation procedures for initiating programs. Those programs which are implementable in a shorter period of time should result in greater tangible benefits to the Army.

Analysis of Evaluation Results

General

Appendix B contains data sheets for all project submissions obtained during this study with the evaluations indicated per the criteria described earlier. Within this analysis section, breakdowns of the submitted projects according to state-of-the-art and ROI assessments are presented.

State-of-the-Art Analysis

A breakdown of the project submissions by helicopter subsystem based upon our state-of-the-art assessments appears in Table 7. Roughly 80 projects out of the 278 seem to fit in well with the MM&T aspect of AVSCOM's activity. Approximately 100 projects seem to fit better in a Manufacturing Development category. These latter programs are typically those which, if funded, will usually require a subsequent MM&T project to carry the development to the implementation stage.

Return on Investment Analysis

Ideally, it should be possible to prepare an accurate ROI analysis for an overall Manufacturing Technology program supported by AVSCOM. The ROI should be sufficiently attractive to merit support from the various groups in the Army which pass judgment on the overall program. An effort was made to do just that. Table 8 shows a distribution of all project suggestions according to projected ROI. However, a review of projects revealed that of the 80 projects which can truly be classified as MM&T programs, 55 have enough cost data to be considered in the analysis.

TABLE 7. STATE-OF-THE-ART STATUS OF PROJECT SUGGESTIONS

Subsystem	State of Art							Total
	R	D	C	B	A	Q	Other	
Airframe	9	35	13	6	1	--	--	72
Engine	22	33	18	11	1	3	3	91
Rotor	11	31	13	6	--	3	6	70
Drive	14	8	5	2	1	1	2	33
Support Equipment	8	1	1	--	--	--	1	12
Totals	64	108	50	27	3	7	19	278
Distribution, %	23	39	18	10	1	3	6	

where

R = Projects seems to be aimed at research more than MM&T

D = Projects would be manufacturing development in nature, requiring further effort to reach MM&T stage

B&C = Projects aimed at bringing a current development to implementation

A = Project needed to qualify for production

Q = Project needed to qualify in new aircraft

Other = Denotes software oriented studies and/or projects not fitting this or other classifications.

TABLE 8. DISTRIBUTION OF ALL PROJECT SUGGESTIONS BY COST REDUCTION POTENTIAL

Expected Return of Army Investment	No. of Projects	Airframe	Engine	Rotor	Drive	Equipment
>7:1	6	2	3	1	0	0
4:1 to 7:1	34	16	8	6	3	1
3:1 to 4:1	43	11	18	10	4	0
2:1 to 3:1	69	19	22	17	9	2
<2:1 (OR UNKNOWN)*	126	24	40	36	17	9
Total	278					

* Many projects and ROI's estimated to be below 1:1.
At least 20 were between 1:1 and 2:1.

A very rough estimate of the average MM&T project funded by AVSCOM is about \$300,000, based on a sampling of several projects in each category. This would mean that

$$55 \times 300,000 = \$16,500,000 \text{ in Army investment during the FY period 1977 to 1982.}$$

Of these 55 projects, 21 are considered to have potential for returning at least 2:1 and the others are estimated as follows:

17 between 3:1 and 4:1 ROI

13 between 4:1 and 7:1 ROI

4 at 7:1 ROI or greater.

The very approximate "worst-case" ROI calculation then would be:

$$21 \times 2 \times 300K = \$12,600,000$$

$$17 \times 3 \times 300K = 15,300,000$$

$$13 \times 4 \times 300K = 15,600,000$$

$$4 \times 7 \times 300K = \underline{8,300,000}$$

$$\text{Total Savings } \$51,800,000.$$

Thus,

$$\frac{51,800}{16,500} = 3.1:1 \text{ ROI.}$$

This seems to be the general level of return on investment that AVSCOM can expect during the 5-year period starting in FY 77. These 55 projects can be categorized as follows:

Category	<u>2:1 - 3:1</u>	<u>3:1 - 4:1</u>	<u>4:1 - 7:1</u>	<u>>7:1</u>
Airframe	6	4	6	1
Engine	6	5	4	2
Rotor	6	6	2	1
Drive	<u>3</u>	<u>2</u>	<u>1</u>	<u>0</u>
	21	17	13	4 .

It should be kept in mind that these ROI values could be somewhat conservative. Nevertheless, it is doubtful that the ROI on AVSCOM's total M&T program will exceed 3:1 on the projects as a whole, not at least until after 1982 when the savings continue on the aircraft under production contract. This is why it will be so important to be sure that any cost saving development gets applied in other Army systems (not only helicopters). For example, the advanced fiber winding techniques developed for helicopters may be found to apply nicely to certain Army missiles. This is how the Army can count on maximum return on its investment in advanced M&T projects.

RECOMMENDED TECHNICAL GUIDANCE FOR AVIATION
MANUFACTURING TECHNOLOGY PROGRAM

General

In the preceding technical guidance sections, cost drivers which affect helicopter acquisition and operating costs were examined and manufacturing technology projects suggested by helicopter manufacturers and users were evaluated. The goals of the remainder of this report will be to assimilate the information and results obtained from the preceding two tasks in order to formulate appropriate "thrust" actions that AVSCOM could undertake toward the benefit of producing lower cost and/or improved performance helicopters and to recommend an effective overall program plan for accomplishing these actions during the next 5 years.

It should be noted that it is extremely difficult to predict individual manufacturing technology project requirements over a 5-year period because new manufacturing developments, ideas and problems are identified every year. This will be especially true during the coming 5-year period when several new aircraft systems will be coming into the Army inventory. This points up the need for a flexible Manufacturing Technology program wherein new developments can be incorporated and individual projects are not "locked-in" years in advance. On the other hand, it does not negate the need for an overall plan of action. Although it may be difficult to define individual projects, overall Manufacturing Technology needs should remain fairly constant over the coming 5 years. Consequently, the first major task in this section will be to define those overall Manufacturing Technology needs.

It should also be noted that it is a difficult task to formulate a coordinated overall plan for advancing the state-of-the-art in a variety of Manufacturing Technology areas through projects which are individually aimed

at specific hardware manufacture. On the other hand, it would be difficult to recommend pursuit of a Manufacturing Technology area without Army requirements (in the form of specific required components). Consequently, a second major task in this section will be to define not only overall Manufacturing Technology needs but to determine how these needs apply to specific helicopter subsystem and component manufacture.

If the Manufacturing Technology "needs" discussed above are now redefined as Manufacturing Technology "thrusts" which AVSCOM should initiate, then the third major task of this section becomes to formulate a 5-year technical guidance plan which encompasses Manufacturing Technology thrusts in general technology areas as well as in subsystem manufacture.

Major Technical Thrusts by Area of Technology

General

Based on the cost driver input and the evaluations made of individual projects suggested by the contractors and subcontractors, 17 major recommended thrusts by technological area were defined. These major technical thrusts are listed in Table 9.

It is also informative to review the distribution of project suggestions supporting each thrust area; the percentage distributions appear in parentheses after each thrust in the table. It should be noticed that a relatively low percentage of project suggestions can occur within a given technical area for a variety of reasons. For example, contractors are not apt to suggest a great number of projects in the area of repairability and maintainability, even though efforts in this area can have major impact on life cycle cost.

More detailed discussions of the individual thrusts are presented in the sections which follow.

TABLE 9. MAJOR TECHNICAL THRUSTS
(Distribution of Project Suggestions)*

Composites (Mostly Organic Composites) (23%)
Joining (Metallic and Organic Composites) (13%)
Repairability/Maintainability (6%)
Computer Applications in Manufacturing (6%)
Quality Control, Nondestructive Testing (6%)
Reduced Part Count (6%)
Net Shape Processing (7%)
Hot Isostatic Processing (HIP) (7%)
Production Ready Tooling (7%)
Materials Related Developments (7%)
Forging (4%)
Casting (5%)

*A project suggestion applicable to more than one major thrust is included in the percentages for all thrusts to which it applies.

Composites

Encouraged by the impressive successes of composite structures in helicopter rotor blades and in some secondary structural applications it is understandable that designers' attentions would turn to potential applications of composites in other secondary and primary structures. This is evidenced by the applications shown for composites in Figure 8 for the YUH-61A UTTAS airframes. Of the project submissions reviewed by the Battelle staff, over 100 have related to the application of composites in rotors and airframe structures. However, the opportunity to apply composites in transmission housings seems worthy of in-depth trade studies. Entire sections are being currently made from layed-up and cured composites which are most often fiberglass reinforced resins or epoxy matrices with or without honeycomb cores such as Nomex. The advantages of composites have become evident. Besides the well-known mechanical properties of composites, the following are examples of particular importance:

- Drastic reduction of the machining and associated power requirements inherent in conventional metallic materials
- Conservation of materials due to reduction in material wastage since laminated composites are built up to shape rather than machined down to size. The materials utilization factor with composites is impressive
- Significant potential reductions in weight (30 to 75 percent) resulting in lower inertia and lower operational power requirements for operational systems
- Improved fatigue lives of 3 to 10 times that of conventional materials, and provisions are possible for fracture tolerance--significantly improving safety

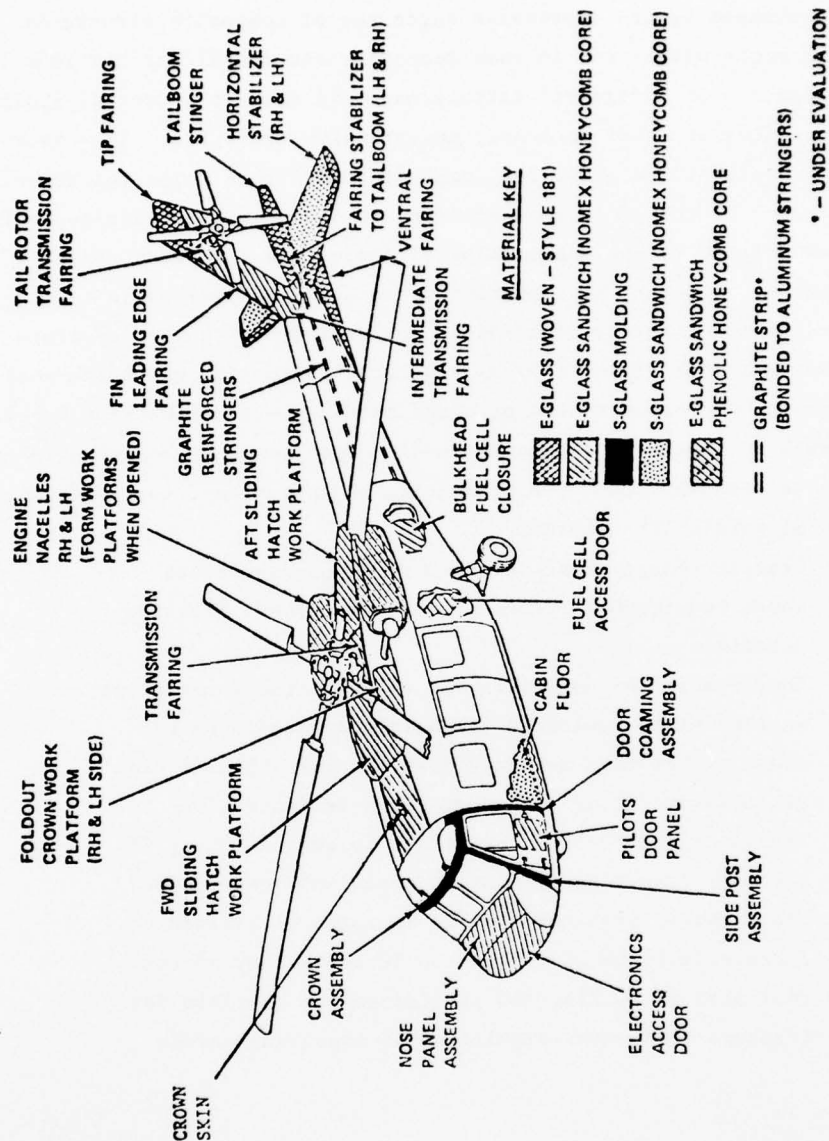


FIGURE 8. CURRENT MAJOR COMPOSITE MATERIAL APPLICATIONS ON YUH-61A UTTAS AIRFRAME

- Virtual elimination of corrosion problems
- Automatic and semiautomatic equipment has been developed for tape layup onto rotating mandrels to form relatively simple shapes (round and rectangular tubes, cones, etc.) which can be formed into more intricate configurations.

The lay-up of broadgoods into more complex shapes is usually done in sections by hand. Attempts to automate the lay-up of broad goods and/or tape in such cases have only been marginally successful to date. This means that the labor content of composites must remain high in the manufacture of many complex structures. This coupled with variability in workmanship and the high cost of nondestructively inspecting composite structures, tends to discourage manufacturers from designing helicopter structures in composites.

It should be pointed out that nonmetallic composites still represent a relatively small percentage of the fly weight of helicopters (estimates range up to only 5 percent). The balance of components are still manufactured from conventional metals. Further opportunities exist for applying composite structures, assuming in-depth cost/strength trade studies prove favorable. On the balance, it is reasonably clear that the next few years will witness a growing use of composites in helicopter construction. The most innovative applications of composites will emerge as the designer gains confidence in their use. Furthermore, the more innovative designers will begin to design structures specifically for composites rather than as substitutes for metal structures. This means that, for example, designers will also be aware of fabrication and cost limitations for composites, and design for these from the outset.

Pultrusion has been used successfully to produce shapes having some degree of transverse fiber orientation using new approaches to feed the fiber into the required orientation prior to drawing. It is conceivable that many primary and secondary structures formerly made from

metallic structural basic shapes, can be made in composites using the pultrusion process. It is also foreseeable that such structural shapes will become increasingly assembled along with the broadgoods to form subassemblies.

One problem in the application of composites is the large number of combinations of matrices and fibers.

It is recommended that emphasis should be directed to optimize and subsequently standardize on a fewer number of matrices and fiber combinations so that the materials can be purchased in larger quantities resulting in more economically attractive composite structures.

There is no question but the attributes of composites have been demonstrated well in the manufacture of rotor blades, and even when the costs of such blades are equal to or more than the conventionally constructed blade, the longer service life and improved reliability can justify the cost difference.

A feature of the application of composites in helicopters is that composites represents a method for reducing part count and for producing net shapes. However, the areas of quality control and repairability become important considerations when applying composites to critical structures.

The state of the art of preparing composite airframe structures to date is rather complex because almost every new structure converted from metal requires various combinations of lay-up and/or wrapping prior to curing. New weaving methods (e.g., Dow-Weave) add a new dimension to the directionality of properties which can be expected from reinforced plastic composites. Thus, it will continue to be important for AVSCOM to support projects related to the specific applications for composites, especially programs aimed at reducing labor content and for assuring quality and reproducibility. On the other hand, it may not always prove cost effective to convert metal structures to composites. There are some potential applications where such conversions to composites hold little promise for increasing

aircraft performance and/or cost effectiveness. It would, therefore, be timely and appropriate for the Army to prepare a Manufacturing Cost/Design Guide which can be used by designers and manufacturing engineers to assist in deciding whether to use composites or not.

The following summaries present the findings on composite materials:

► Objectives of Composite Technology Thrusts

- Significant reduction (60 percent) in factory man-hours
- Reduction in cost of facilities
- Reduced energy requirements
- Improved buy-to-fly ratios
- Use of composites will reduce effect of foreign influences, e.g., aluminum.

► Opportunities to Reduce Cost of Composite Structures

- Improved cutting and handling techniques
- Increased use of automatic tape layup
- Self-contained tools
- More rapid cure of matrices and adhesives.

► New Design Concepts

- New design concepts needed, with both conventional and advanced materials, for ease of inspectability to reduce costs
- New design concepts needed to develop and produce "advanced" composite structures costing less than

riveted aluminum structures and with significantly extended lives - make today's materials last longer

- New design concepts needed so that new requirements can be met at no increase in cost, i.e., affordable performance.

► Braiding, Weaving, and Pultrusion

- Filament or tape winding equipment for production of complex ballistically tolerant structures such as tail-booms with:
 - Significantly reduced design and labor hour content
 - Hybrid fibers
 - Low part-count
 - Drastic reduction of joints
 - Potentially lower cost than riveted aluminum
- Develop three-dimensional weaving techniques and equipment for panelized structures to reduce close-out member cost, reduce weight, improve reliability and improve ballistic tolerance
- Develop braiding methods for producing complex ducting in glass-reinforced plastics selectively reinforced by graphite fibers
- Develop pultrusion machines to produce basic shapes, e.g., closeouts and stringers, designed for greater standardization throughout fuselage and subassemblies. Hand-fitting and subsequent high NDT costs will be drastically reduced.

► Sandwich and Geodesic Configurations

- Develop special sandwich core designs and associated manufacturing equipment to provide insensitivity to field damage experienced with lightweight aluminum honeycomb configurations
- Production equipment required for ballistically tolerant composite components and structural subassemblies employing discontinuous or geodesic configurations. Examples are:

- Driveshafts
- Bell-crank levers
- Tail-booms
- Other fuselage parts.

► Thermoplastics, Microwave Curing and Molding

- Develop total manufacturing systems to permit exploitation of fiber-reinforced thermoplastics, i.e., from unidirectional tape to innovative structural concepts tailored for thermoplastics, to the recycling of scrap material. These materials show promise of competing with riveted aluminum sheet secondary structures
- Develop microwave curing procedures and equipment producing thick composite parts cost - competitively
- Composite molding method with chopped fibers to produce hatches, access doors, and brackets
- Methods required to move large uncured parts in fabrication facilities. Today handlings sometimes involves several individuals.

► Methods of Reducing Cost of Graphite/Epoxy Parts

In some cases, weight will also be reduced.

- Employ metallic interleaves in regions of high stress gradients and fasteners
- Employ hollow fasteners
- Use of metallic edge-members (close-outs) might reduce fastener count
- Study lower temperature curing epoxies, i.e., modified epoxies at 225 F or less (provides more rapid heating and cooling rates, lower electricity costs, and also lower tooling costs may be possible)
- Where applicable, use graphite-cloth/thermoplastics in preference to epoxies because of lower fabrication costs
- Develop new cost-effective configurations with unidirectional members, e.g., around cut-outs.

► Low-Cost Design/Manufacturing Methods Required for Metal-Matrix Composites

- To produce metal-matrix composites tubular structures (unidirectional B/Al) with integral end-fittings for landing gear, engine mounts and similar primary structures. Examples are:

Adhesively-bonded laminated tubes from foil
Electron-beam welded tubes from rolled sheet

- For metal-matrix composite (B/Al) rotor-blade spars.

Examples are:

Extrusions
Adhesive bonding

- To develop diffusion bonding and other processes to selectively reinforce forged components with unidirectional metal-matrix composites to reduce machining costs and energy requirements while providing fracture tolerance.

► Lower Cost Tooling Required

- Integrally heated, cooled and pressurized familing of tooling for prototype and production structures providing:
 - Reduced lead time
 - Cost reduction through labor savings
 - Energy conservative concept
 - Cocuring opportunity for shell-liner concepts
 - Reduced possibility for extensive hardware losses (as in autoclave)
 - Increased rate of production
- But integrally heated tooling requires strong materials and process/tooling/designer interface. Need to explore and identify all potential applications to reduce cost and wastage
- Furthermore, integrally heated tooling requires more extensive thermal analysis to:
 - Optimize heat-transfer efficiency
 - Develop innovative heating/cooling concepts.

► Rotor Blades

- Production equipment required to permit designer to create composite blades built-up from smaller elements reducing possibility of large losses during assembly phase. Examples of such elements are:
 - Pultruded/wound cells
 - Wound cells
 - Pultruded trailing edge closures
 - Pultruded/wound tail-rotor spars
 - Braided spars
- Develop extensions of rotor-blade manufacturing technology to enable composites to be used with both low cost and advanced fibers, e.g., strategic reinforcement of glass-fiber reinforced plastic blade, reducing cost. Equipment must provide flexibility to designers
- Tape-layup machines to circumvent autoclave by providing simultaneous curing of tape
- With strong preliminary design-MMT interface, develop lightweight, highly efficient concepts for blade roots which enable automated methods to be used. Hand-layup of root connections need to be avoided in future blade designs
- Equipment required to reduce the cost of machining complex contours in nomex honeycomb cores for rotor blades.
- Paint Stripping - Simplify stripping of paint from rotor blades (particularly composite blades). This is presently a very expensive operation.
- Hand-Finishing - Reduce the hand-finishing required for helicopter rotor blades. Hand-finishing could be

responsible for 40 to 50 percent of the blade cost. On some blades, 50 hours are required for hand-finishing.

- Simpler Lay-up Equipment - There is a need to develop simpler, lower-cost tape and fiber-laying machines which are design oriented. A problem is that companies may not be able to afford the machine time or the cost of large machines that have been developed. A number of smaller design-oriented machines are required in carrying out operations of more limited scope. The importance of the interface between design concept generation and machine developments is obvious.
- Joining of Metallic Spars - Methods need to be developed to rapidly join metallic spars. These spars are sometimes fabricated from sheet, brakeformed cold to form a tube and then hot-formed. Laser welding and plasma arc welding were mentioned. It was understood that at least one company employs roller welding. A major cost-driver is the setup time for welding spars and attention should be focused on reducing this element of cost. There seemed to be a need to develop design concepts that enable steel spars to be formed more consistently. Here again is an example of the importance of the design/materials and process interface.
- Bonding of Steels - There is a need to develop more effective methods of surface treatment of steels for highly reliable adhesive bonded joints for blade applications. Reference was made to the work of U. S. Steel on the pretreatment of surfaces for commercial adhesive-bonded structures. In the mid-50's, when alternatives to brazed stainless-steel sandwich structures

were sought, R & D was conducted on methods to improve the properties of adhesive-bonded joints in 17-7PH. More work is justified in this area.

- Curing Techniques - The excessive curing times for composite rotors was mentioned by several helicopter manufacturing engineers. The following approximate curing times were noted:

250 - 300-lb rotor; curing time 8 - 12 hours

750-lb rotor; curing time 16 hours.

More work is, therefore, required on direct heat-transfer tooling and radio-frequency heating

- Control of Fiber/Resin Ratio - There is a requirement to develop methods to control the fiber/resin ratios (as placed and cured) and, hence, achieve repetitive values for filament wound blades. It was stated that \pm percent can be achieved with tape. Controlling the end item during the cure is a problem pointed out by one participant.

► Composite Drive Shafting

- Further develop filament winding equipment for hybridized composite transmission shafting, e.g., graphite and Kevlar-49, providing:

Increased stiffness meaning fewer bearings and supports

Notch insensitivity and the multiplicity of load paths result in ballistic tolerance

Tailorability and efficiency of material gives
lower weight/unit length
Potential weight and also cost savings approxi-
mately 40 percent.

► Transmission Housings

- Provide opportunity for innovative design approaches utilizing manufacturing technologies discussed, i.e., B/A1 tubular truss structure with Gr./Ep. case.

► New Concepts for Actuating Levers

- While some of the innovatively designed levers, e.g., geodesic bell-cranks, do meet the ballistic tolerance requirements, new concepts are necessary which are more compatible with the severe space limitations in helicopters. These concepts may require alternative methods of fabrication. Because of these space limitations, a problem similar to missile design, hybrid systems of metallic and polymer matrix composites are a possibility.

► Honeycomb Cores

- Cost of Machining - Lower cost methods are required for the frequently complex machining operation of shaping cores for blades.
- Cost of Cores - Aluminum honeycomb is really the only core which helicopter companies can afford, but radar imaging rule out metallic cores. Furthermore, composites

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tend to absorb moisture and might promote corrosion of metallic cores.

Nomex honeycomb is more expensive than aluminum (5-7 to 1). The modulus of Nomex honeycomb is not ideal. There is, therefore, a need for a new type of low-cost, high-performance honeycomb such as in glass-reinforced plastic. If the latter material went into extensive production for honeycomb cores, it was felt that a considerably lower cost could be achieved than for Nomex. Other geometrical configurations for sandwich cores should be explored.

► Filament Winding of Skins

- There is a need for innovative high-speed approaches in filament winding so that the cost of glass fiber reinforced plastic structures can be reduced. Some manufacturing engineers felt that filament winding developments essentially stopped 20 years ago! Optimized filament wound deck-house facings first as a large cylinder which is then cut and laid flat onto foam cores to form the sandwich panel.

► Blade Metallic Leading - Edges

- Further work is required on low-cost, nonmetallic abrasion-resistant leading edges of low-radar cross section.

- A problem is the edge treatment titanium leading edge sheets. These components are formed and bonded, and it is understood that considerable time and cost are required to chamfer the edges of the sheet.
- The forming of nickel leading edges is time-consuming. It is believed that 12-16 hours were mentioned for this operation. The tooling is expensive, warping and trimming are problems, and field replacement procedures do not exist.

The foregoing comments serve to illustrate why the project staff is strongly recommending that Composites be considered a major thrust and that this broader thrust can be broken down into several appropriate subthrusts each directed to a component or family of components.

As will be shown in a later section on funding guidance, a 5-year budget for composite technology represents over 20 percent of the total being recommended. However, continued attention to verify cost reduction accomplishments should be the subject of continued attention by the AVSCOM staff to insure return on investment is being experienced.

Joining

The act of joining structures and components by mechanical fastening, welding, brazing, and/or adhesive bonding accounts for over half of the labor involved in assembling turbine engines, rotors, drives, and airframes. Hence, joining is a very important cost driver--not only from the high labor content but because of the additional high labor required to assure joint quality.

One source indicated that there are well over 50,000 total fasteners in a large helicopter and that over 4000 standard and nonstandard fastener shapes, sizes, and types are used in the helicopter industry. Thus, efforts to both eliminate and standardize on fewer types of fasteners are worthwhile. This point has been made repeatedly by previous studies* evaluating cost drivers so will not be emphasized here. The fact that specialized or nonstandard fasteners cost from five to twenty times more than similar "standard" fasteners provides a built-in incentive to standardize as much as possible.

With the help of computers it has become increasingly practical to arrive at fastener standards throughout the aerospace industry. Thus, the Battelle team sees no reason for the Army to support studies related to the manufacturing of lower cost fasteners. On the other hand, a joint Army-Air Force program aimed at computer-aided fastener selection could prove valuable. A low-level effort is currently underway to develop a specification (Mil-Std-1515) which will be aimed specifically at identifying standards for the selection of fasteners for the aerospace industry. The Air Force may soon increase its effort in this area; however, to the Battelle team's knowledge, the potential effort does not include computer-assisted fastener

* Marchinski, L.J., "Design to Cost at Work for Helicopter Systems", AIAA Paper No. 74-962, presented at 6th Aircraft Design Flight Test and Operations Meeting, Los Angeles, California, August, 1974.

*"Army Helicopter Cost Drivers", Harold K. Reddick Jr. Eustis U.S. Army Air Mobility Research and Development Laboratory.

selection -- something which could be included, especially if the Army and Air Force shared the cost.

The labor required in installing fasteners requires careful study to identify labor-saving ways of automating the installation of rivets and bolts. This subject was discussed with most contractors, who agreed that modularized riveting devices should be developed to permit installation of a number of rivets simultaneously.

As an alternative, two companies suggested a combination of adhesive bonding and riveting (Rivet-Bonding) using roughly one-third the normal number of rivets to augment adhesively-joined panels. In structures using this process the adhesive would provide both bond strength and a barrier to moisture migration. This method seems to be more adaptable to accomplishing higher joint reproducibility than Spot Weld-Bonding, a process coupling adhesive bonding and spot welding. A continuous problem with the latter process is that a high percentage of weld nuggets contain porosity as a result of the breakdown of the adhesives, which have a tendency to contaminate the weld zone; this occurs especially when the adhesive layers (hence gaps) vary due to variations in fit-up tolerances.

The joining of sections of composite structures continues to represent an important area; especially when joined to metallic structures. Dimensional changes which occur when honeycomb stiffened structures are cured can lead to variations in the forces required to fit up the faying surfaces. This problem can lead to difficulty in matching up the fastener holes and to variations in residual stresses in joints. Designing the faying surfaces to be more flexible represents one alternative, but this can lead to the need for adding supplemental stiffening caps to the joint area. A variety of joints are being studied by several contractors. One such joint which could be used (after further evaluation of its merits) is an interwoven fiber hinge joined with adhesives and subsequently stiffened with semiround or quarter round caps.

About 70 projects involving joining technology were suggested by prime contractors as representing approaches to important problems. About 30 of these projects pertained to joining of airframe structures, about 25 were related to rotor and drive assemblies and approximately 15 were identified in relation to turbine engines. About half of the projects are related to composites, which in turn is another major thrust. Because partial or complete use of adhesives reduces the number of fasteners used in assembly, advanced joining technology also represents a method of reducing the part count which is still another major thrust. This gives further emphasis to the need for important attention by the Army to joining technology.

Repairability and Maintainability

The thrust in repairability and maintainability relates to effecting repairability and maintainability in production aircraft, solving maintenance problems that can be traced to manufacturing problems and developing improved procedures for maintenance and repair as they relate to Depot manufacturing operations.

It is well recognized that helicopters require greater maintenance than fixed wing aircraft of comparable size because they are more complex, are subjected to consistently higher operating stresses and the dynamic systems operate continuously at near design limits. Vibration also contributes to the maintenance problem in helicopters, imposing both expected and unexpected forces on the dynamic components as well as the structural components. Another factor creating difficulty in maintenance and repair is that the subsystems are packaged in a congested manner within helicopters making many components, and subcomponents difficult to reach during normal maintenance.

The helicopter operational environment is an important factor also in the maintenance problem. They are typically operated close to the ground, exposing them to a more hostile environment than fixed wing aircraft. Landing and take-off from unprepared fields, causing the ingestion of solid particles and debris, leave the engines vulnerable to more rapid wear-out. These are but a few of the many reasons why the project staff recommends repairability and maintainability as being a major thrust in AVSCOM's future planning. Maintenance and parts account for 56% of the total life cycle for a typical helicopter*; it is important to identify those areas where this cost can be affected.

* Army Helicopter Cost Drivers USAAMRD-L-TM-7, August, 1975, Eustis Directorate, USA Air Mobility R&D Lab.

As might be expected, the contractors contacted in this survey acknowledged the importance of maintenance and repairability on their respective aircraft and/or subsystems. However, there were only a few projects relating directly to maintainability and repairability described to the Battelle staff as being appropriate for AVSCOM funding, partly because such programs have apparently not received a great deal of attention from AVSCOM.

One of the reasons for this seems to relate to the fact that the cost benefit of maintenance and repair related programs are difficult to pin down in specific terms and they are not part of the first costs.

One area of the composite major thrust includes the suggested use of fiber-reinforced thermosetting plastics which could improve the repairability of composite structures substantially.

In turbine engines the repairability problems are largely found in the turbine portion of the engine where blades corrode and/or break out during service. The most modern helicopter engine (T700) is designed with integral compressor "blisks", rather than the more conventional dovetail slot-type assembly used in earlier engines. This means that better methods for joining the blades by diffusion bonding or perhaps friction welding are necessary to replace blades on a damaged blisk; otherwise, the entire assembly may have to be scrapped.

In transmissions one of the key factors in maintenance is the wear-out of seals at various shaft openings and subsequent loss of transmission fluid. Heavier greases are being used by the Corpus Christi Army Depot in reworking transmissions, with no adverse effect of the heavier greases, and the practice results in longer mean time between subsequent overhauls.

In the construction of conventional airframe skin-stringer design for the fuselage, the rivets that fail can be removed and replaced with

nuts and bolt assemblies. Adhesively bonded structures, on the other hand, would probably require an additional riveting and/or bolting once the bond joints separate due to the rigorous environment helicopters encounter. Thus, an effort to reduce the first cost of joining structures by adhesive bonding can increase the cost of maintenance and repair because the faying surfaces must be cleaned, refitted, and either rebonded with adhesives or in some instances drilled and riveted together.

In a study conducted by Cook* it was found that the data being used in analyzing maintenance history on specific components was not always precise. However, he and his associates were able to identify a number of important areas where the man hour requirements were quite high in maintaining some helicopters in comparison with others. The study identified the components of current inventory helicopters which contribute most of the high man hour cost of maintenance. The report quantified the problems in terms of maintenance time. Thus, the Production Technology Branch of AVSCOM could find it important to establish even stronger communication ties with the Corpus Christi Army Depot in order to stay on top of maintenance problems.

From the standpoint of contractor response, repair and maintenance was mentioned as part of or as the main subject of over 30 potential projects suggested for AVSCOM future planning. It is interesting to note however, that less than 20 percent of such R&M efforts relate to composites where the problems of joining are most dominant. It is our opinion that R&M of composites will represent a vital part of AVSCOM's future efforts, assuming that the steadily increasing use of composites in helicopters will continue.

* Cook, T. N., "Maintainability Analysis of Major Helicopter Components", August 1973, U.S.A. AMRDL Technical Report 73-43.

Computer Applications in Manufacturing

The advent of low-cost computers has brought tremendous capability for applications in the manufacture of helicopters. According to representatives of companies contacted, the list of applications continues to grow as each firm gains increasing confidence in:

CAD - Computer aided design

CAM - Computer aided manufacture

CAI - Computer aided inspection

In design, CAD programs have been effective for

Preparation of shop drawings

Preassembly check out

Design of blade forms.

and some early work is under way to apply CAD to airframe structures, gear profiles, and in material selection. With the growing bank of manufacturing cost information on materials and processes within each company, it is expected that computers could soon be useful in speeding up cost trade-off studies prior to finalizing designs for components and/or subassemblies. It appears that CAD programs are progressing reasonably well at most airframe builders and identification of potential efforts with high return on Army investment is difficult.

On the other hand, further developments of the CAM applications of numerical control (N/C) machining, cutting and welding, and tape/fiber layup represent opportunities for cost reduction. For example, emphasis on N/C machining of blisks for the T700 engine using multiple-spindle machines should save considerably over the indexing, single-spindle machining methods now practiced. This development is also a good example of where CAD/CAM activities interface with the major thrust aimed at developing production-ready tooling.

Production tape or fiber winding of structures often require one-of-a-kind machines designed for specific applications and including cams, worm gears, and various slides to provide multiple axis capability in laying down tape/fiber onto suitable mandrels; these type machines are not numerically controlled. On the other hand, the Automated Tape Layup System (ATLAS) at Boeing-Vertol is a numerically controlled machine designed specifically to be extremely versatile so that it could be used for determining the extent to which tape layup can be automated and determining the designs of subsequent production machines.

There is a general belief that small N/C systems tailored to narrow ranges of part sizes are more efficient than either large, "universal" machines or conventional, single-purpose machines, when used in production.

Efforts either under development or early application in the promising area of CAI include:

- On-machine dimensional inspection of parts during machining
- Inspection of blade forms
- Nondestructive evaluation (NDE) of metallic and nonmetallic (composite) structures, components.

Inspection of composite structures either after manufacture or during service represents one of the most important challenges for NDE systems. Most single frequency systems (ultrasonic, eddy-current) are capable of detecting changes and/or differences in response but are not very diagnostic. They pick up both real and false "defects". For this reason the simple tap test is still preferred by most firms in checking for disbonds or delaminations in composite structures.

However, mini-computers are being used with increasing success in evaluating the response to multiple frequencies simultaneously to help distinguish false from real flaws in components. So far, most of the effort has applied to essentially homogeneous materials. However, there

is a growing confidence that computer-aided systems will be developed for composite structures. Since inspection costs may vary anywhere from 5 percent to well over 50 percent of the manufacturing costs (especially for composite structures), it is believed that some emphasis during the next 5 years should be directed to this important area of CAI.

The complex mathematics involved in analyzing stresses in structures has required long manual calculations usually carried out on portable calculators. Two firms have indicated that it is becoming increasingly practical to take into account stress distributions in increasingly complex structures through computer-aided stress analysis (CAS).

There is growing confidence that future aircraft structures can be designed to the point of shop drawings with computers. Reasonably effective systems are already in use at General Electric, Allison and other companies for design, drawing, and subassembly check out.

This same area of CAS has been demonstrated to various degrees in the design and preparation of tooling for sheet forming, stamping, cutting, forging, and extrusion. The programs take into account such variables as applied stresses, tool deflections and part spring-back to make the tooling very close to correct the first time, thus eliminating much trial-and-error in tool machining.

The Army should continue to experience good return on investments in future programs aimed at applying computers to manufacturing.

Quality Control

The area of quality control has been identified as a major thrust for the Army's consideration because (among other reasons) of DoD's emphasis on "adequate performance for reasonable cost". As indicated earlier, quality control is an important cost driver. Final inspection costs represent only a portion of any quality control operation applied to aircraft structures and other hardware. There are numerous in-process inspection operations which start from the raw materials and continue through virtually all manufacturing steps. There is general agreement that the costs are high but difficult to pin down.

The implementation of both basic and advanced quality control (QC) and nondestructive inspection (NDI) methods is accepted practice throughout the helicopter industry. This area includes not only NDI techniques that are used to assure the quality and reliability of individual critically loaded components, but QC tests used to sample the batch quality of less critical components. NDI techniques used commonly in the helicopter industry include radiography, ultrasonic, penetrant, and magnetic particle tests, eddy current, and "tap tests". The more common QC tests employed are dimensional measurements, selective destructive tests, and batch chemical analysis.

Advancing technology, reliability, and performance requirements have, in general, out-paced the development of QC/NDI techniques. Hence, there is a need to develop and implement more sophisticated and efficient QC/NDI systems. QC/NDI technology gaps have come to exist for many reasons. High system performance with the associated stringent reliability requirements have placed increasing demands on QC/NDI for "flaw-free", close-tolerance components. The development of new design concepts and methodology together with the associated more complex material systems (such as advanced composites) has resulted in components that are extremely difficult (if not

impossible) to inspect reliably using existing QC/NDI techniques. This has resulted in redundant inspection of often questionable or undeterminable reliability.

In efforts to improve component reliability, substantial destructive testing is often employed. In addition, the amount of QC/NDI required per component and the number of components requiring QC/NDI has increased, as has the complexity of the inspection techniques, resulting in substantial operator interaction in the inspection process and the interpretation of its results. This has resulted in increased manual inspection labor and a variable inspection reliability, primarily due to operator involvement in the interpretation of inspection data.

The net effect of this technology gap has been to increase inspection costs and to cause a questionable and often undeterminable inspection reliability. Labor intensive inspection with the associated increasing labor costs and redundant inspection practices has resulted in nondestructive QC/NDI costs accounting for as much as 30 percent of the total costs for many components.

Many advanced design components on the drawing board and in prototype phases will be extremely costly, if not impossible, to inspect using techniques available today. Therefore, it is important that more advanced and automated inspection techniques be developed and implemented.

Presuming that there is excellent success in eventually reaching a very high level of confidence in the nondestructive evaluation of composite structures, it is foreseeable that designers will be able to take fuller advantage of the strength capability of composite structures. Perhaps design factors of less than 2:1 can be considered rather than using the safety factors of over 4:1 which is current practice.

Other than the computer-aided inspection efforts described in the last section, the specific quality control related projects suggested by contractors which seem to stand out are those related to the nondestructive evaluation of composite structures.

This area is receiving considerable attention by contractors in their respective IRAD programs. Examples of efforts include

- Use of optical fibers scattered throughout fiber-reinforced structures (lack of optical response at a root point indicates some discontinuity of unknown severity or location)
- Use of lead-type glass fiber scattered throughout the fiber reinforcement (broken fibers noticed upon radiographic inspection is another sign of a discontinuity)
- Composite blades are maintained under positive air/gas pressure during service (leakage is a sign of a discontinuity of unknown severity or location)
- Attempts have been made to standardize on the sound changes occurring during simple "tap testing" to help distinguish frame disbonds from other type of "intentional" discontinuities (e.g., honeycomb structures) or bond zones containing too much adhesive/resin.

The Army's growing commitment to the use of composite structures makes it important to develop truly diagnostic methods for distinguishing between harmful flaws and harmless discontinuities.

For this reason we are strongly recommending that virtually all programs undertaken to evaluate and apply composites include significant attention to NDI procedures.

There are well over 35 suggestions for projects related to quality control -- mostly for composite structures. However, there are still many other inspection problems related to metallic components:

- Location and evaluation of flaws in hollow blades
- Location of small cooling passages in cast blades
- Assurance of bond quality after welding, brazing, and especially after diffusion bonding of superalloys and titanium.

For advanced turboshaft engines one of the most important problems stems from high rpm. Low-speed balancing systems do not always give the desired engine balance especially for taking into account harmonic and/or impedance effects of localized imbalances which can cause the total rotor assembly to distort slightly along the axis of rotation. Closely spaced shaft bearings are used to control this condition. However, the blade/shroud clearances are extremely tight which can lead to abrasion of the blade tips and/or shrouds. While blade tip erosion leads to some improvements in local balance, the greater clearances lead to some undesirable losses of engine efficiency. Ideally, the engine rotor would be balanced in all sections rather than having localized offsetting imbalances (the current system). All engine manufacturers contacted agreed that the application of a computer-aided multiplane, multispeed balancing system would help them reach the ideally balanced turbine rotor.

Based on maintenance experiences at Corpus Christi Army Depot, the quality assurance techniques for checking out components during scheduled and unscheduled maintenance requires important attention. This is again especially true for composite structures. Many "retire" or "reuse" decisions are made based on personal experience of individuals rather than on the basis of diagnostic testing. This also applies to some extent in transmission repair where diagnostic tests are needed to help decide when or when not to retire gears, bearings, and other critical components.

Estimates made at the Corpus Christi Depot suggest that a high percentage of parts, which might otherwise have a much longer service life, are replaced as a precaution rather than based on diagnostic evaluation.

Thus, attention to the in-service quality control of components will be important especially as the newer models (AAH, UTTAS, CH-47) arrive on the scene at Corpus Christi.

It is often difficult to estimate the direct benefits of increased component or system reliability, but if inspection reliability is improved such that redundant inspection could be eliminated and automated inspection systems implemented, it is estimated that inspection costs (that are upwards of 30 percent for many components) could be reduced by a factor of 3. Other direct and indirect benefits that are to be realized include a lower component rejection rate, lower materials and fabrication costs (assuming component over design because of uncertain inspection reliability), elimination of most destructive testing, and better feedback to in-process quality control.

Reduction of Part Count

Since high part count has been identified as a leading cost driver, it is understandable that a major thrust should be directed to reducing the inventory of parts required to assemble each helicopter. The action is needed to reduce the labor involved in handling and installing components. A sampling of some current actions to reduce part count include

- Commonalizing left- and right-hand parts where possible
- Standardization of fastener selection
- Substituting adhesive joining for riveting
- Combining adhesive bonding with reduced numbers of rivets/bolts
- Using unitized composite structures in place of conventional skin stringers
- Welding engine components together (gears, shafts) in place of fasteners and clamps.

Over 30 project areas have been suggested toward the goal of reducing part counts beyond the more than 100 suggested projects related to the use of composite structures. Yet many of the suggested projects have a tendency to increase labor content while making the single parts or while reducing the fasteners. In the latter case, the need for precise fit-up and expensive jigs and fixtures accompanies most all of the adhesive joining activity. This all involves labor for making the adjoining surfaces more precise, for making the jigs and fixtures, and for applying and curing the adhesives.

There was general agreement that, given the present state of the art in composite component manufacturing, the use of composites as a means of reducing part count was not always in the interest of economy in the

manufacture of airframes. An exception to this is when composites are used in the manufacture of a small number of prototype helicopters where "soft" tooling can be made simply from castable or moldable material to form a few parts. However, once in production, conventional construction is now usually considered by airframe manufacturers to be more economical.

In the areas of turbine engines and transmissions, reduced part count comes up in proposed approaches to friction welding shafts to gears and disks to replace the spline/bolt/clamp systems now more commonly used to assemble the shafts. Suitable projects aimed at producing one-piece shaft gears (or disks) are worthy candidates for Army support.

Efforts in part reduction complement and interface with efforts in the other major thrusts of joining and composites, and further descriptions of individual actions to reduce part count appear in the sections for those thrust areas.

Net-Shape Processing

There is almost unanimous agreement between the producers of airframes and engines that there should be a major initiative included in the AVSCOM manufacturing technology activity aimed at producing "net" shapes -- parts rolled, forged, extruded, cast and/or pressed from powders to (or very close to) the final contours. Several examples of suggested efforts include

- Precision Forging of Radial Impellers
- Precision Casting of Radial Impellers
- Precision Forging of Transmission Gears
- Isothermal Forging of Turbine Disks
- Precision Roll Forming of Compressor Blades
- Hot Isostatic Pressing of Components for Airframes, Rotors and Engines from Powders
- Close Tolerance Casting of Rotor Hubs
- Precision Extrusion of Structural Shapes.

Proponents of net-shape processing cite substantial material savings over several hundred ship-sets or engines where typical machining losses to chips currently represent anywhere from 4 to 12 times the finished part weights. The logic of supporting appropriate manufacturing technology programs is often overwhelmingly favorable. Excessive chip losses are definitely a major cost driver in the manufacture of hardware. However, when the Battelle staff asked further questions about why net-shape processing isn't more widely used now, the answers almost always came down to tooling costs, process development costs and small production quantities.

As an example, the current method for producing forged structural components usually involves the sinking of generously contoured dies and subsequent forging of generously contoured "envelope" shapes followed by machining away 60 to 90 percent of the original forging weight to yield the final parts.

At first glance, this appears to be extremely wasteful. Yet much of the machining involves drilling of holes, machining of slots, grooves, and other reentrant areas which would be impossible to forge (and still remove the parts from forging dies) -- whether precision forgings or "envelope" forgings. Considering this aspect (with the exception of simple shapes such as blades and flat disks), it is doubtful that a major campaign to precision forge a wide range of structural parts would reduce the metal losses (to chips) below a level of about 50 percent. Yet the incentive for net shape is still there. Consider a 1000-pound structural forging machined to a 150-pound finished part. This represents an 85 percent metal loss to chips. If the same part could be "net" forged to a weight of 300 pounds, the metal loss would be reduced by 700 pounds -- a tremendous savings in material and machining.

These generalities skirt the real issue though. In most cases, the tooling for precision or net-shape forging is far more costly than for the generously contoured forging because more die stagings are required and the dies wear out faster. Furthermore, the shop development time is often on the order of four to six times greater for precision forging. Finally, the production rates are usually much lower, especially for isothermal forging or "Gatorizing". This means that the forging companies must recover their costs associated with such efforts and they quote unit costs for precision forging at two to six times higher than for conventional forgings. This has to be balanced against the machining costs saved at the customer's plant. These high tooling and development costs are experienced most when forgings are purchased in relatively small quantities.

The manufacturing technology for precision forging is reasonably well understood and within the state of the art for such items as

- Aluminum Structural
- Titanium Blades
- Superalloy Blades
- Steel Gears and Cams

- Superalloy Disks (Isothermal Forging)
- Titanium Disks (Isothermal Forging)
- Small Steel Structural.

Yet few of these are purchased by helicopter manufacturers as precision forgings. Why? The main reason is that the typical purchase quantities are not large enough to amortize the high tooling and development costs within the first few runs.

This is where AVSCOM could take an active role in furthering the production application of net-shape forming. It could essentially support the early manufacture of tooling and process refinement of precision forgings which would then be applied to subsequent purchases of forgings (where the longer ranging cost-benefit is foreseeable over several production runs). If this isn't done, it is doubtful that the contractors and forging suppliers will choose net processing for any parts purchased in quantities of less than about 250 parts per run.

In an attempt to arrive at approximate quantities of forged gears needed to justify changing from conventional practice to precision forging practices, contacts were made with such companies as

- Burgess-Norton Company
- Gleason Works
- Wakefield Bearing Company
- Eaton Corporation
- Federal Mogul Corporation.

These companies are all active in precision forging of gears on a production basis. The general consensus is that run quantities must be greater than 5000 gears and, in many cases, higher than 50,000 parts to justify the tooling costs. It should be pointed out that these are low-rpm gears* used in such applications as tractors, riding mowers, snowmobiles and other off-highway equipment. Thus, precision forging of gears for helicopter

*The dimensional tolerances on precision-forged gears are generally 2 to 3 times those for cut gears. This means that they can cause greater noise when operating at especially high rpm.

transmission service would probably be hard to justify when considering the relatively small production runs more typical of helicopter transmissions.

It would also seem that justification of precision gear forging programs will have to be based more on the superior performance aspect (longer life) rather than on savings in first costs.

Precision casting of semicritical and critical components seems to be a logical alternative to forging. Examples of high performance castings produced on a production basis include:

- Turbine blades (Ni-base)
- Turbine vanes (Ni-base)
- Shrouds (Stainless steel)
- Compressor casings (Alloy steel)

There are several other potential applications for precision castings including

- Control linkages (Titanium investments)
- Rotor hubs (Titanium)
- Compressor blades (Titanium, alloy steel)
- Radial compressor wheels (Titanium, alloy steel)
- Compressor disks (Alloy steel)
- Turbine disks (Superalloys)

From our findings, none of these are yet qualified for production application in Army helicopters.

One of the chief concerns in the application of castings is that for reproducibility and quality -- castings generally contain some amount of macro- or microporosity due to shrinkage, and these are not always in the same regions of the parts. Thus, there has been an understandable reluctance to use castings in critical applications.

However, hot isostatic processing (HIP) of castings has now entered the scene, where the castings are exposed to high pressures of 15,000 to 20,000 psi in autoclaves heated up to 2200 F (depending on alloy).

Originally, HIP was developed for densifying compacts from metal powder and has been used for a number of years for this purpose. The application of HIP to castings is relatively new. However, it has already been qualified for production in the treatment of cast superalloy blades at two engine manufacturers. In one case, HIP is used mainly to treat production castings which failed to meet radiographic standards and were held on Material Review (MR). After HIP treatment, about 90 percent of such MR castings pass radiographic inspection. Thus HIP has been shown effective in upgrading castings.

It seems logical then to consider applying HIP to any new critical component converted from forgings to castings. This would be done to provide more reproducible properties and to give the designers greater confidence in the use of castings in critical locations. Later experience should provide enough data to help decide when the HIP operation can be dropped from the manufacturing cycle as a further cost reduction. Further discussion of such effort is contained in the following section on hot isostatic processing.

Hot Isostatic Processing

Over 30 potential cost-reduction projects identified would result in substituting either metal powder parts or castings for forgings in rotors, drives, turbine engines and airframes. There is little doubt that such approaches represent potential performance problems in critical applications, considering the recognized low density of powder-metal parts and porosity in castings.

However, hot isostatic processing has been demonstrated effective in densifying and raising the fatigue performance of parts made by either technique. The main question then relates to whether the properties meet the design requirements.

According to engine builders, the expected cost savings in the application of castings (subsequently HIP treated) to turbine components vary from 10 percent to nearly 40 percent in comparison with forging costs. The HIP-casting route seems to offer the greatest payback because castings can be produced closer to final part dimensions than most forgings (exception -- blades).

From the technical standpoint, the process of compacting powder by HIP to produce final parts is not expected to give the best properties, not at least until the powder metallurgy components are brought to full density by forging (for example, isothermal forging). The preparation of critical components from powders without forging is now at an earlier manufacturing development stage (for example, HIP of T700 turbine disks sponsored by AVSCOM) and will require further effort prior to acceptance.

By contrast, the Army could encourage further conversions from forging to HIP-castings under MM&T -- provided the cost reductions continue to appear favorable. For example, the casting of smaller titanium components for European helicopters is considered state of the art and it is true that titanium castings are less costly than forgings (especially in relatively small quantities). However, no one contacted felt comfortable

in applying castings to the manufacture of larger titanium parts (such as rotor hubs, airframe structurals and turbine disks), at least until extensive experience is gained with smaller castings.

On the other hand, the real potential payoff for HIP-castings (estimated savings in millions) is in the substitution of lower cost, near-net castings for these larger components, which are usually machined extensively to less than 10 percent of the forging weight.

It seems logical then for the Army to initiate programs aimed at gaining experience with smaller cast titanium parts, such as control rod ends (of which there are more than 30 per aircraft). These rod ends are currently specified as forgings and seem to be good candidates for investment casting. If an appropriate project is undertaken by AVSCOM, it is recommended that the resulting castings be treated by HIP to be sure the casting quality is at its best.

Assuming favorable experience is gained, the casting could then be applied to progressively larger parts when the cost payoff is increasingly attractive. The application of HIP to such castings should be considered part of the manufacturing development effort until the soundness of castings can be brought to acceptable levels.

Giving consideration that the Air Force Manufacturing Technology Division is also planning to support projects related to the application of HIP to castings, it is important for both service groups to maintain close liaison to give maximum opportunity for synergism.

Production-Ready Tooling

Over the next 5 years, prime contractors will begin building UTTAS and AAH at relatively low production rates. Since the budgets for these aircraft are often relatively fixed and with the current tight money and peace-time conditions, it is conceivable that total aircraft constructed on the contracts could drop by perhaps 25 to 50 percent over the contract period. Current plans call for about 470 AAH and 1100 UTTAS aircraft with rather low delivery schedules at the outset. Thus, it is foreseeable that the prime contractors will use as much "make-do" tooling as possible, an action which could cause the manufacturing costs to remain nearly as high during production as for the original prototype aircraft.

With these probabilities in mind, there are some overall long-term economies which can be realized by having production-ready tooling and/or machinery available at the outset of production. Examples of candidates include

- Automatic tooling for riveting fuselage structures
- Multiple spindle N/C facilities for machining compressor blisks
- Automatic tape/fiber lay-up equipment
- Integrally heated/cooled dies for forming and curing of composite structures -- especially rotor blades
- Inertia welding equipment for attaching shafts to transmission gears.

Over 50 projects aimed at development of and/or installation of production-ready equipment were suggested by contractors contacted in this survey. Over half of these suggested projects were related to the goal of reducing the high labor content in the manufacture of composite structures.

Based on these observations, it is logical that some projects aimed at installing production-ready tooling be supported with MM&T funding over the next 5 years -- especially after the final contractors are selected for each of the advanced helicopters.

Materials-Related Development

Materials related development is identified as a distinct technical thrust aimed largely at implementing currently developed advanced materials in helicopter components and subsystems. The thrust of current developments specifically related to advanced materials involve such areas as

- Substitution of newer, stronger and/or higher temperature-resistant alloys in turbine engines
- Application of closer-to-finish part making methods using advanced materials
- Precision forging of advanced material gears, disks, and airframe structurals
- Close-to-finish casting of components for engines and structurals
- Upgrading quality of advanced material castings by application of hot isostatic processing
- Computer-aided design and manufacture of advanced-material components
- Improvement of quality control procedures for newer materials
- Joining of titanium and heat-resistant alloys.

Most all of these activities have been aimed at reducing manufacturing costs, applying advanced materials processed by advanced manufacturing techniques and/or increasing service lives of metallic components. The attention being directed to the substitution of organic composites for metals in many of the secondary and some selected primary structures demonstrates an important trend in helicopter manufacture; materials-related developments are further described in the composites thrust section. Some of the future efforts for metallic materials-related developments follow.

The newer T-700 engine is considered to represent many new challenges for existing heat-resistant alloys during peak operating rpm. This has brought increased attention to the needs for such manufacturing development activities as

- Application of directional solidification to improve creep/resistance of heat-resistant alloys used in turbine blades/vanes
- Application of improved coatings for vanes and blades
- Application of internally cooled and transpirationally cooled turbine blades cast with internal cooling passages
- Development of abradable yet effective seal materials for turbine shrouds
- Application of hot isostatic processing (HIP) to improve the integrity of cast turbine disks, blades, and vanes
- Development of effective methods for replacing damaged or missing blades onto turbine disks machined with integral blades (blisks).

The limits of temperature resistance are being reached in turbine engines, bringing attention to the potential application of ceramics for bearings. However, there were no urgent requirements brought to the attention of the Battelle project team. Currently used high-speed steels are providing reasonable bearing life in all of the rig testing programs discussed. However, field experience has demonstrated that there still are unexpected low bearing lives being experienced in the field. A brief review of several engine bearing failure analyses performed at the Corpus Christi Depot.

indicates that more than half of the bearing failures are due to lubrication failure and/or metallic debris in the oil.

Several hundred gear failures of various types have been experienced at the Corpus Christi Depot. More than 75 percent of the failures are reportedly due to galling and pitting, which in turn are usually attributed to lubricant failure. Correlations with the surface finish of the gear teeth have not been very clear. When transmissions are rebuilt at the Depot, it is common practice to change lubricant from the oil types to heavier greases. This seems to extend the lives of transmissions more than any significant change in the surface finish on the gears.

It is always a good practice to continually evaluate new gear alloys for potential life improvements; however, there are other areas to be looked at. For example, there seemed to be general agreement that the "superfinish" required on many of the gears was unnecessary for achieving maximum gear life. At least three of the suppliers of helicopters agreed that it would be important to reevaluate the requirement for the superfinish and consider using a run-in finishing method instead. A disadvantage of the current dimensional and surface finish requirements for transmission gears is that the rejection rates are rather high -- nearly 15 percent in one case. Yet the gears may well have been good candidates for the run-in finishing method (more commonly being used successfully at the Corpus Christi Army Depot and supplied in matched sets). Such gears are most always replaced as matched sets anyway rather than to replace one new gear along with a used gear.

In summary, the thrust of materials-related MD and MM&T programs during the coming 5 years should be largely aimed at applying cost-effective, advanced manufacturing methods to existing materials.

Forging Technology

Forging technology is identified as a major thrust for two major reasons:

- Forging represents the manufacturing methods which provide the highest level of metallurgical quality in hardware components
- Because forgings require expensive tooling and processing costs they are generally more costly than other forms of hardware (castings, weldments).

Thus, the approaches to producing lower cost forgings represent an important area for continued attention by AVSCOM.

Over the past decade both the Army and the Air Force have supported nearly 100 different projects concerned with various aspects of forging technology. Some of the projects have resulted in some important accomplishments in

- Isothermal forging of turbine disks
- Precision forging of compressor blades
- Close tolerance forging of structures from titanium and steel
- Precision forging of transmission gears.

The programs have included developments in forging lubricants, die materials, and other processing technologies which have indirectly led to improved efficiency in forging of other critical components. It is perhaps worth reviewing the reasons why so many important advances in forging technology have come as a result of Government-sponsored programs.

From a purely business standpoint the premium high quality, custom forgings field is not a growth industry, except in times of national crisis. Business levels in the forging fields are generally cyclic, but the industry is indispensable to the private and government welfare in producing reliable hardware for aircraft, missiles, steam power, turbine electric power and many

other industries. Thus it is important for advancements to be made continually to improve forging technology.

With perhaps three or four exceptions, custom forging companies do not ordinarily conduct broad developmental programs aimed at optimizing their processes for maximum quality at minimum cost. For example, automated handling is seldom seen in custom forge shops. This is partly explained by the general aim to maintain versatile facilities permitting the forging companies to bid on forging of wide variety of part shapes for a diversity of customers.

Another characteristic of most custom forging companies is that they do not make it a practice of exchanging technical information about developments in forging specific parts or processing details. This also explains why there are very few technically useful publications about forging practices issued by the custom forging firms.

The isothermal forging work sponsored by the government is a good example of the situation where advanced processing development would probably not be applied by industry without Government support. The logic of this situation is easily explained. The forging company which quotes price and delivery on a part usually lists tooling costs separately, and when an order is placed the finishing dies become the property of the customer. Thus, the customer has to pay for the tooling directly. When purchase quantities are small, the unit cost allowed for tooling can be several times the balance of the unit costs. This results in an obvious incentive for the purchasing company to aim at minimizing tooling costs. In the case of isothermal forging the cost of nickel-base or refractory metal dies, heating elements and the insulated back-up tooling can represent several times the cost of conventional dies made from lower alloy steels. Therefore the decision to apply isothermal forging or other processes that increase tooling costs is more in the hands of the customer than in the control of the custom forging shop. The part designer should be encouraged to finalize the design enough so that little or no change is needed in the expense of isothermal forging dies

before using them on subsequent orders. If such a commitment is made, the isothermal forging process represents an attractive method for reducing machining operations, metal losses, and total costs. Here is a good example where unit costs of initial forgings, for example in the first year, may be substantially higher than in subsequent orders, mainly because of the need for amortizing the costly tooling. Thus, the payoff in applying isothermal forging may not come until the second or third year of the procurement cycle.

The Government has funded several programs aimed at characterizing or improving the mechanical properties obtainable from the forging alloys. It is important to have extensive mechanical property data available before selecting the new materials for a particular application. Programs aimed at generating extensive design data are valuable because they permit the designer to make informed decisions in materials selection.

The review of many advancements in forging technology directly attributable to Government support provides convincing evidence of the key role that both the Army and the Air Force have played.

Forging technology interfaces with other major thrusts including

- Net Shape Processing (precision forging)
- Production-ready tooling (preparation of dies for precision forging)
- Computer design in manufacturing (design of forging dies in forgings)

More detailed discussions of individual actions are described in those thrust sections.

Over 20 specific forging projects were suggested by industry during this survey. Most relate to the further application of precision forging as a means of reducing input material and machining cost. It should be further emphasized that the potential pay back in forging to near net shapes will probably not come during the first year but should come during subsequent production orders.

Casting Technology

Casting technology is identified by the Battelle staff as a major thrust because there are so many potential opportunities for cost reduction in the use of premium quality castings in helicopters. High quality is already being experienced in the production of superalloy turbine vanes and blades vacuum cast to net or near net shapes. Titanium castings are increasingly being used on European helicopters, and, indeed, many are purchased from American casting firms.

Titanium components in helicopters vary in size from the small clevice type end fittings on control rods to turbine blades to the very large rotor heads on certain helicopter models (CH-47 and UTTAS, for example). These are all currently made from forgings. One company suggested that a program aimed at producing close-to-finished castings for rotor heads would represent an attractive cost reduction potential of several hundred dollars per aircraft. However, the Battelle staff feels uncomfortable about applying castings in such large, critical components at least until some highly favorable experience is gained with smaller castings such as the control rod ends. It is probably true that applying castings to the smaller components would not save nearly as much per helicopter. However, if such components are cast and possibly treated by hot isostatic processing, it is possible to gain a growing confidence in the use of castings to progressively larger parts and perhaps eventually to large rotor heads.

It is considered appropriate to begin such effort now, with the eventual payoff coming within 5 or 6 years when industry confidence is increased to the point where designers will turn to premium titanium castings for critical structural components. There are more than 30 control rod ends used in typical helicopters. Thus, experience with casting in evaluating these in-flight hardware can come rather rapidly if such a program is undertaken soon.

There is still room for improvement in the casting of turbine components. Estimates vary that between 5 and 20 percent of the castings must be reworked or scrapped due to such factors as variations in dimensions of internal cooling passages, variations in root/blade twist relationships and in overall part-to-part uniformity. Some blades are scrapped due to internal voids located by radiographic techniques.

Over 25 problems or potential solutions involving castings were recommended by representatives of industry. Most of these relate to casting of turbine components. At least two engine manufacturers have already adopted the use of HIP as a means of reducing scrap losses for metal porosity. The porosity is reduced or eliminated by the combination of high temperature and high pressures developed by the HIP cycle. Furthermore, this process is now considered qualified for production, giving credibility to the application of HIP/casting in a larger number of applications. Most such application would, of course, require some extensive evaluation. Further discussions centering on casting technology appear in the section on net-shape processing.

Important Technical Thrusts by Helicopter Subsystem

General

Utilizing the evaluation criteria described previously and the grouping of suggested projects into major thrust areas, the most important technical thrusts to be considered in each of the four helicopter subsystems are listed below.

<u>Airframe</u>	<u>Engine</u>	<u>Rotor</u>	<u>Drive</u>
Composites	Materials-Related Development	Composites	Joining
Joining	Casting	Production-Ready Tooling	Composites
Reduction of Part Count	Joining	Joining	QC/NDT
Production-Ready Tooling	Net Shape	QC/NDT	Forging
R and M QC/NDT	R and M	CAD/CAM	CAD/CAM

These thrust areas represent those which had the highest degree of commonality among the project suggestions reviewed and evaluated as having worthy effects on helicopter cost. As would be expected, the technical emphasis differs for each subsystem.

In lieu of extensive narrative discussion, Tables 10, 11, 12, and 13 contain the summation of our findings concerning typical problem areas and thrust actions for the solution of these problems. More detailed discussion of problem areas and thrusts are given in the previous section concerning major technical thrusts by area of technology. It should be noted that these problem areas/actions are not all-inclusive, but only those areas with a high degree of commonality.

TABLE 10. IMPORTANT TECHNICAL THRUSTS - AIRFRAMES

Overall Technical Emphasis		
Reduction of Part Count and Labor Costs Through the Development of Production Ready-Tooling for Manufacture of Composite Structures Including Attention to Joining and Repairability		
Typical Problem Areas	Major Thrust Area	Thrust Actions
<ul style="list-style-type: none"> • High labor content of composite structures • Unreliable NDE of composite structures • High cost of curing composite structures • Cutouts and holes in composite structures cause localized weaknesses • High cost of specialized composite materials • Insufficient data on fiber reinforced thermoplastics to permit implementation • Joining of composite structures to metallic structures 	COMPOSITES	<ul style="list-style-type: none"> • Molding of integral fiber-reinforced structures • Integrally heated dies for curing structures during lay-up • High speed microwave techniques for curing • Application of molded, reinforced thermoplastics • Production of airframe structurals by braiding/pultrusion • Production of low-cost lightweight cores using honeycombs, foams • Automated broadgoods lay-up for relatively simple shapes • Emphasis on quality control/NDE of composite structures • Improved structural designs tailored to composites (geodesic) • Standardization of materials for composites • Continuing attention to economics in use of composites

TABLE 10. (Continued)

Typical Problem Areas	Major Thrust Area	Thrust Actions
	COMPOSITES	<ul style="list-style-type: none"> Improved joining methods for joining composite to metallic structures Design guides describing when and when not to use composites A thorough assessment of applications and methods for joining composites with adhesives and/or mechanical fastening
<ul style="list-style-type: none"> Panels with aluminum honeycomb require extremely close fit-up and costly anticorrosion measures High assembly costs for small production runs Excessive labor involved in the manual riveting of structures 	JOINING	<ul style="list-style-type: none"> New close-outs for simplified assembly Broader application of rivet bonding Broader application of adhesive bonding Develop tooling for automated riveting of production panels/assemblies Adhesive joining of composite structures

TABLE 10. (Continued)

Typical Problem Areas	Major Thrust Area	Thrust Actions
<ul style="list-style-type: none"> • Large number of components <ul style="list-style-type: none"> - Rivets and other fasteners - stringers - Left and right hand parts • Large number of part designs 	PART COUNT	<ul style="list-style-type: none"> • Application of unitized composite structures • Standardization of components • Redesign L&R-hand parts for interchangeability • Conduct cost trade-off studies between conventional and composite structures
<ul style="list-style-type: none"> • Tooling for small quantities, while initially less costly, results in high labor costs when used for production • Airframe forgings require extensive machining to chips 	PRODUCTION READY TOOLING	<ul style="list-style-type: none"> • Determine where production-ready tooling is a good investment over total production orders, for example: <ul style="list-style-type: none"> precision forging automatic riveting automatic tape/fiber lay-up
<ul style="list-style-type: none"> • Airframe structures are difficult and costly to repair/replace 	R&M	<ul style="list-style-type: none"> • Identify where components and sub-assembly R&M can be improved
<ul style="list-style-type: none"> • The influences of different types of discontinuities in composite structures are not well understood 	QC/NDE	<ul style="list-style-type: none"> • Conduct studies related to the effects of "defects" in composite structures

TABLE 11. IMPORTANT TECHNICAL THRUSTS - TURBINE ENGINES

<u>Overall Technical Emphasis</u>		
Improved Performance of Advanced Materials Cast and Hot Isostatic Processed to Near-Net Shapes to Reduce Costs of Turbine Components. Production Ready Tooling Will be Especially Important to the T-700 Program as Will Suitable Joining Processes.		
Typical Problem Areas	Major Thrust Area	Thrust Actions
<ul style="list-style-type: none"> • Solid particle erosion of compressor blading • Bearings are exposed to temperature approaching limits of materials • Wrought materials require excessive machining to chips 	MATERIALS CASTING NET SHAPE FORGING HIP	<ul style="list-style-type: none"> • Material conservative processing <ul style="list-style-type: none"> - Casting of T-Blades (DS, HIP) - Casting of C-Blades (HIP) - Casting of stator components - Precision forging of disks - P/M plus HIP of T-Disks • Improved coating for blades • Application of Heat-resistant bearing materials
<ul style="list-style-type: none"> • High maintenance/repair costs • High cost of balancing Total Rotor Assemblies • Designing, contouring, and inspecting blades represents a high cost area 	JOINING R&M QC/NDE CAM	<ul style="list-style-type: none"> • Improved repair methods <ul style="list-style-type: none"> - Weld build-up versus blade replacement - Diffusion bonding • Computer aided <ul style="list-style-type: none"> - Design - Manufacture - Inspection • Automated multiplane rotor balancing • N/C machining of Blisks

TABLE 12. IMPORTANT TECHNICAL THRUSTS - ROTOR

<u>Overall Technical Emphasis</u>		
Continuing Improvements in Fiber Reinforced and Honeycomb Composite Structures, Including Important Attention to Production-Ready Tooling for Manufacture, Joining, and Quality Control (Production and In-Service) as Applied to Main and Tail Rotor Blades for Increasing Reliability and Reduced Costs		
Typical Problem Areas	Major Thrust Area	Thrust Actions
<ul style="list-style-type: none"> • High labor content in lay-up of composite rotor blades • Testing of composite rotor blades (including NDE) 20 to 50 percent of manufacturing costs • High cost of multiple curing cycles for composite blades • High cost of nonmetallic blade cores • Joining of blade/root represents a quality • Contouring and trimming of blade forms represents high labor costs • Joining of blade/root represents a quality problem 	COMPOSITES	<ul style="list-style-type: none"> • Low-cost spars from braided/pultruded structures • Application of lower cost core materials <ul style="list-style-type: none"> - Honeycomb - Injected foams (tail rotors)
	PRODUCTION TOOLING	<ul style="list-style-type: none"> • Development of integrally heated blade bonding press • Automatic and semiautomatic tape lay-up machines for production
	CAD/CAM	<ul style="list-style-type: none"> • Composites with lower curing temperatures
	QC/NDE	<ul style="list-style-type: none"> • Microwave (RF) curing • Automatic broadgoods lay-up machines
	JOINING	<ul style="list-style-type: none"> • Standardization of composite materials • Develop in-process inspection systems for assuring adequate joints between components • Diffusion bonding of rotor hub forgings

TABLE 12. (Continued)

Typical Problem Areas	Major Thrust Area	Thrust Actions
<ul style="list-style-type: none"> • High labor content in maintenance of main rotors • High chip losses in machining of rotor hubs • Titanium casting technology not advanced enough to permit application in rotor hubs/components 	<p>R&M</p> <p>NET SHAPE PROCESSING</p> <p>FORGING</p>	<ul style="list-style-type: none"> • Develop alternate sources for elastomeric bearings • Continued effort in applying HIP to cast parts to insure quality adequate for critical applications • Improved methods for manufacturing nose caps: <ul style="list-style-type: none"> - Sheet metal forming - Electroforming • Multiple-ram forging of rotor hubs

TABLE 13. IMPORTANT TECHNICAL THRUSTS - DRIVE

Overall Technical Emphasis		
Development of Improved, Low-Cost Drive Components and Composite Housing, Including Important Attention to Precision Forging, Nondestructive Testing, and CAD/CAM		
Typical Problem Areas	Major Thrust Area	Thrust Actions
<ul style="list-style-type: none"> • Flexibility and non-uniformity of magnesium housings • Seal leakages • High chip losses in machining gears • Current gear materials still lack sufficient resistance to scoring, pitting, galling, and tooth fracture • High maintenance/repair costs • Gear tolerances difficult to achieve • Inspection costs for gears very high (over 10 percent) • Gears require high finishing costs to provide "super-finish" • Assembled shaft gears require numerous fasteners and fittings 	COMPOSITES	<ul style="list-style-type: none"> • Application of integrally stiffened structures to housing to improve rigidity
	R&M	<ul style="list-style-type: none"> • Development of improved seals for longer life
	NET SHAPE	<ul style="list-style-type: none"> • Bearing recondition programs • Precision hot forging of gears to minimize chip losses
	QC/NDT	<ul style="list-style-type: none"> • Modularized construction of housings for improved reproducibility and stiffness
	CAD/CAM	<ul style="list-style-type: none"> • Evaluate various gear finishing methods and designs for lowest cost yet effective performance
	PART COUNT	<ul style="list-style-type: none"> • Computer-aided inspection of gear forms to reduce inspection costs
	JOINING	<ul style="list-style-type: none"> • Improved gear contour design for longer life • Inertia welding of shafted gears to reduce part count

Recommended Five-Year Technical Guidance Plan

As a basis for establishing program funding guidance, the results of project review were used. As indicated earlier, some 55 projects reviewed were considered to be implementation oriented representing an MM&T budget of about 18.3 million dollars* for the five-year period between FY-77 and FY-82. Combining both the MM&T and the Manufacturing Development activities for the same period, the five-year budget would be established at about \$65.9 million, including programming for Accelerated Implementation. Table 14 indicates an approximate breakdown according to the four categories under consideration.

TABLE 14. FIVE-YEAR FUNDING GUIDANCE - MANUFACTURING DEVELOPMENT AND IMPLEMENTATION

Airframes	\$ 33.1 million	50 percent
Engines	16.9 million	26 percent
Rotors	7.9 million	12 percent
Drives	<u>8.0</u> million	12 percent
Five-year total	\$ 65.9 million	

Tables 15, 16, 17, and 18 show suggested program duration, funding and timing requirements for both MD and MM&T funds for the suggested thrust areas in each subsystem. Overall thrust areas served as the basis for conclusions concerning projects or types of projects which were then prioritized as having the most potential for success based on the criteria already defined. As indicated earlier, this general methodology provided the basis for the program investigation and the findings, in turn, formed the base on which this budget was estimated.

* Includes \$16.5 million plus about \$1.8 million for program management.

If this plan is adopted, it means that about \$18.3 million would go directly to MM&T; about \$15 million will go to MD programs which, in turn, will be followed by about \$20.4 million in follow-on MM&T programs; Accelerated Implementation programs account for the remaining \$12.2 million. It must be repeated that the establishment of these budgeting figures is based upon those projects deemed to represent potential worthy benefits to the Army. As new developments occur, the specific actions could change. Furthermore, these charts represent an independent analysis and in no way should be construed as Army policy.

TABLE 15. RECOMMENDED TECHNICAL AND FUNDING GUIDANCE - AIRFRAME

SUBSYSTEM	COMPONENTS	TECHNICAL THRUST AREA	ACTIVITY GUIDANCE						FUNDING
			FY77	FY78	FY79	FY80	FY81	FY82	\$1000
AIRFRAMES	FUSELAGE SECONDARY STRUCTURES PRIMARY STRUCTURES	COMPOSITES (ORGANIC)							
		JOINING	-----	-----	-----	-----	-----	-----	600
		MOLDING OF STRUCTURES	-----	-----	-----	-----	-----	-----	600
		INTEGRAL DIE CURING	-----	-----	-----	-----	-----	-----	800
		RF CURING	-----	-----	-----	-----	-----	-----	400
		THERMOPLASTIC APPLICATIONS	-----	-----	-----	-----	-----	-----	700
		PULTRUSION, FIBER BRAIDING	-----	-----	-----	-----	-----	-----	400
		LIGHTWEIGHT CORES: HONEYCOMB	-----	-----	-----	-----	-----	-----	400
		FOAMS	-----	-----	-----	-----	-----	-----	600
		AUTOMATED TAPE LAY-UP	-----	-----	-----	-----	-----	-----	1,500
		AUTOMATED BROADGOODS LAY-UP	-----	-----	-----	-----	-----	-----	1,500
		NDT/QC	-----	-----	-----	-----	-----	-----	1,500
		FLUID JET TRIMMING	-----	-----	-----	-----	-----	-----	100
		BROADGOODS IMPROVEMENTS	-----	-----	-----	-----	-----	-----	500
		STRUCTURAL DESIGN IMPROVEMENTS (GEODESIC)	-----	-----	-----	-----	-----	-----	300
		ECONOMIC ANALYSES (AVSCOM)	-----	-----	-----	-----	-----	-----	300
		STANDARDIZATION OF MATERIALS	-----	-----	-----	-----	-----	-----	100
		JOINING	-----	-----	-----	-----	-----	-----	*
		COMPOSITES (ABOVE)	-----	-----	-----	-----	-----	-----	*
		RIVET BONDING	-----	-----	-----	-----	-----	-----	500
		AUTOMATED RIVETING	-----	-----	-----	-----	-----	-----	300
		REPAIR AND MAINTAINABILITY	-----	-----	-----	-----	-----	-----	1,000
		COMPUTER APPLICATIONS: DESIGN	-----	-----	-----	-----	-----	-----	500
		INSPECTION	-----	-----	-----	-----	-----	-----	500
		MANUFACTURE	-----	-----	-----	-----	-----	-----	1,500
		QUALITY CONTROL	-----	-----	-----	-----	-----	-----	500
		REDUCTION OF PART COUNT	-----	-----	-----	-----	-----	-----	400
		NET SHAPE PROCESSING	-----	-----	-----	-----	-----	-----	*
		CASTING - SMALL PARTS	-----	-----	-----	-----	-----	-----	500
		LARGE PARTS	-----	-----	-----	-----	-----	-----	900
		FORGING	-----	-----	-----	-----	-----	-----	600
		PRODUCTION READY TOOLING	-----	-----	-----	-----	-----	-----	5,000
		MATERIALS DEVELOPMENT	-----	-----	-----	-----	-----	-----	*
		FORGING TECHNOLOGY	-----	-----	-----	-----	-----	-----	*
		CASTING TECHNOLOGY	-----	-----	-----	-----	-----	-----	*
		MANUFACTURING COST/DESIGN GUIDES	-----	-----	-----	-----	-----	-----	400
		ACCELERATED IMPLEMENTATION	-----	-----	-----	-----	-----	-----	6,000
		MILITARY REQUIREMENTS	-----	-----	-----	-----	-----	-----	
		FIRE RETARDANT FUEL CELLS	-----	-----	-----	-----	-----	-----	500
		IR SUPPRESSION	-----	-----	-----	-----	-----	-----	1,000
		ARMOR DEVELOPMENT	-----	-----	-----	-----	-----	-----	1,000
		TRANSPARENT ARMOR	-----	-----	-----	-----	-----	-----	500
		CRASHWORTHINESS	-----	-----	-----	-----	-----	-----	500
		LASER TECHNOLOGY	-----	-----	-----	-----	-----	-----	500

--- Manufacturing Development

--- Manufacturing Methods and Technology

* Denotes technical activity; funding given elsewhere

TABLE 16. RECOMMENDED TECHNICAL AND FUNDING GUIDANCE - TURBINE ENGINES

SUBSYSTEM	COMPONENTS	TECHNICAL THRUST AREA	ACTIVITY GUIDANCE						FUNDING \$1000
			FY77	FY78	FY79	FY80	FY81	FY82	
TURBINE Engines	COMPRESSOR	JOINING/REPAIR							*
		BLISK BLADE REPLACEMENT							200
		COMPUTER APPLICATIONS							
		MACHINING BLISKS N/C							800
		INSPECTION OF COMPONENTS							200
		NET SHAPE PROCESSING							
		CASTING OF NET BLADES INCO 718							200
		CASTING (PLUS HIP) OF T1 BLADES							200
		PRECISION CASTING OF CASINGS (PLUS HIP)							500
		PRECISION CASTING ROTORS (PLUS HIP)							500
		ROLL FORMING SEALS							300
		PRODUCTION-READY TOOLING							500
		MATERIALS DEVELOPMENT							*
		IMPROVED BLADE EROSION RESISTANCE							200
	TURBINE	JOINING/REPAIR							*
		BLADE ATTACHMENT							500
		BLADE REPAIR							300
		JOINING SHAFTS TO DISKS							800
		COMPUTER APPLICATIONS							
		AUTOMATED ROTOR BALANCING							1,000
		BLADE INSPECTION (QC)							400
		DISK INSPECTION							500
		CA - MANUFACTURE - VARIOUS							1,000
		CA - DESIGN - VARIOUS							400
		QUALITY CONTROL (QC)							100

TABLE 16. (Continued)

SUBSYSTEM	COMPONENTS	TECHNICAL THRUST AREA	ACTIVITY GUIDANCE						FUNDING \$1000
			FY77	FY78	FY79	FY80	FY81	FY82	
TURBINE ENGINES	TURBINE	REDUCTION IN PART COUNT							*
		JOINING SHAFTS TO DISKS							*
		STANDARDIZE PARTS							100
		NET SHAPE PROCESSING							*
		PRECISION HIP CASTING OF BLADES							300
		HIP-CAST DISKS							500
		P/M-HIP DISKS							300
		HIP-CAST NOZZLES							200
		ROLL FORMING SEALS							600
		HOT ISOSTATIC PROCESSING							*
		CASTING IMPROVEMENTS							*
		P/M ALLOYS							600
		PRODUCTION-READY TOOLING (FOR DEVELOPED PROCESSES)							600
		T-BLADE COOLING SYSTEMS							500
		DISK COOLING SYSTEMS							500
		MATERIAL-RELATED DEVELOPMENT							*
		IR COATINGS							*
		NOZZLE IMPROVEMENT							800
		COMBUSTOR MATERIALS							300
		FORGING TECHNOLOGY							*
		ISOTHERMAL FORGING-- DISKS							300
		CASTING TECHNOLOGY							300
		DS BLADES/ALLOY IMPROVEMENT							200
		ACCELERATED IMPLEMENTATION							3,000

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TABLE 17. RECOMMENDED TECHNICAL AND FUNDING GUIDANCE - ROTORS

SUBSYSTEM	COMPONENTS	TECHNICAL THRUST AREA	ACTIVITY GUIDANCE						FUNDING \$1000
			FY77	FY78	FY79	FY80	FY81	FY82	
ROTORS	BLADES	COMPOSITES (ORGANIC)							
		SPARS	---	---	---	---	---	---	300
		CORES: HONEYCOMB	---	---	---	---	---	---	300
		FOAMS (ALSO TAIL BLADES)	---	---	---	---	---	---	200
		PULTRUSION OF STRINGERS	---	---	---	---	---	---	150
		BRAIDING FIBERS	---	---	---	---	---	---	150
		INJECTION MOLDING	---	---	---	---	---	---	350
		THERMOPLASTIC INSERTS	---	---	---	---	---	---	200
		JOINING AND TRIMMING	---	---	---	---	---	---	*
		BLADE BONDING PRESS	---	---	---	---	---	---	500
		BREAKFORM, WELD TO SPARS	---	---	---	---	---	---	300
		FLUID JET TRIMMING COMPOSITES	---	---	---	---	---	---	50
		MAINTAINABILITY AND QC	---	---	---	---	---	---	*
		NDT OF BLADES	---	---	---	---	---	---	300
		EFFECT OF DEFECTS IN COMPOSITES	---	---	---	---	---	---	300
		REDUCTION OF PART COUNT	---	---	---	---	---	---	*
		NET SHAPE PROCESSING	---	---	---	---	---	---	*
		PRODUCTION-READY TOOLING/CAM	---	---	---	---	---	---	1,200
		BLADE BONDING PRESS	---	---	---	---	---	---	*
		INTEGRAL DIE CURING	---	---	---	---	---	---	*
		N/C BROADGOODS LAY-UP	---	---	---	---	---	---	500
		N/C TAPE LAY-UP	---	---	---	---	---	---	500
		SHEET FORMING NOSE CAPS	---	---	---	---	---	---	300
		ELECTROFORMING NOSE CAPS	---	---	---	---	---	---	300
	HUBS	COMPOSITES	---	---	---	---	---	---	*
		ELASTOMERIC BEARINGS	---	---	---	---	---	---	200
		JOINING/NET SHAPE	---	---	---	---	---	---	*
		DIFFUSION BONDING/FORGINGS	---	---	---	---	---	---	800
		HOT ISOSTATIC PROCESSING	---	---	---	---	---	---	*
		CAST HUBS	---	---	---	---	---	---	500
		P/M - FORGED HUBS	---	---	---	---	---	---	400
		P/M - HUBS	---	---	---	---	---	---	300
		FORGING TECHNOLOGY	---	---	---	---	---	---	*
		CORE FORGING HUBS	---	---	---	---	---	---	100
		ACCELERATED IMPLEMENTATION	---	---	---	---	---	---	1,600

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* Denotes technical activity; funding given elsewhere

TABLE 18. RECOMMENDED TECHNICAL AND FUNDING GUIDANCE - DRIVES

SUBSYSTEM	COMPONENTS	TECHNICAL THRUST AREA	ACTIVITY GUIDANCE						FUNDING \$1000
			FY77	FY78	FY79	FY80	FY81	FY82	
DRIVES	HOUSINGS GEARS BEARINGS SEALS SHAFTS	COMPOSITES							*
		INTEGRALLY STIFFENED STRUCTURE			---				600
		COMPOSITE STRUCTURE					---		300
		COMPOSITE DRIVE SHAFT	---						600
		JOINING							*
		MODULARIZED CONSTRUCTION		---					600
		INERTIA WELDING SHAFT GEARS				---			600
		REPAIR AND MAINTAINABILITY							*
		BEARING RECONDITIONING PROGRAM							200
		SEAL LIFE IMPROVEMENT							500
		COMPUTER APPLICATIONS							*
		GEAR DESIGN AND MANUFACTURE		---					200
		IMPROVED GEAR DESIGN			---				600
		QUALITY CONTROL (ABOVE)							*
		NET SHAPE PROCESSING							*
		PRECISION HOT FORGING			---				400
		CASTING IMPROVEMENT - HOUSINGS							300
		MATERIALS DEVELOPMENT							*
		HEAT-RESISTANT GEAR STEELS			---				300
		CERAMIC BEARINGS					---		400
		ACCELERATED IMPLEMENTATION							1,600
		MISCELLANEOUS							
		DESIGN STUDY - IMPROVED STIFFNESS - HOUSINGS		---					300
		COOLING SYSTEM DEVELOPMENT - HOUSINGS			---				300
		LOW-COST FINISHING - GEARS		---					200

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APPENDIX A

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